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13. ABSTRACT *(Maximum 200 words)*

The research supported by this grant has been focused on the physics relevant to the construction and use of state-of-the-art high current, high brightness, ultra-relativistic electron beams in the energy range from 0.25 GeV to 1.1 GeV, namely, the 1 GeV Duke storage ring system. During this period, the Duke storage ring was commissioned and used for: production of coherent UV radiation (from the OK-4 XUV FEL); production of spontaneous X-ray radiation; and production of a monochromatic gamma-ray beam. A number of very successful theoretical results have been developed and tested. Most objectives specified in the proposal have been achieved. A number of initial objectives for the Duke storage ring have been exceeded during the commissioning of the storage ring and its subsystems. This research has led to the creation of a unique facility capable of producing high brightness electron beams with parameters exceeding initial design goals. These beams have been utilized for ground-breaking achievements with the OK-4 FEL system, including the first-and-only UV FEL in the US and the first-and-only monochromatic gamma-ray beam with tunable energy. Under support of this grant, more than fifty publications have been generated and two Ph.D.s defended.

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Performance and Operation Modes of the Duke FEL Storage Ring

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Abstract— **We present the recent status and performance of the Duke Free Electron Laser (FEL) storage ring. We report a large transverse and energy aperture observed in the storage ring. We describe the consequences of this large aperture on the operation of the storage ring. Several unusual phenomena are reported in this paper, including large amplitude transverse multibunch coherent oscillations (Saturn rings) and beam capture from outside the RF separatrix. We also present the established operation modes for the storage ring, including energy ramping, working point tuning, and different bunch-mode operations to optimize the ring as a synchrotron light source, an FEL, and a gamma-ray source. Finally, we summarize the achieved storage ring parameters since its first operation in November 1994.**

Index Terms—**FEL, storage ring, synchrotron light source.**

I. INTRODUCTION

THE Duke Free Electron Laser (FEL) electron storage ring (Fig. 1) is a light source specially designed with a low emittance and a large dynamic aperture for FEL operations [1], [2]. We started commissioning and initial operation of the storage ring in November 1994 [3] by injecting a 230–285-MeV beam from a linear accelerator. The first electron beam was stored in the storage ring two weeks later. Within two months, we were able to stack the injected beam into the storage ring and ramp the stored beam to 1.0 GeV. Initial operation specifications were achieved in record time, by April 1995.

During 1995, a Russian optical klystron, the OK-4 FEL system [4], was installed and aligned in the south straight section of the storage ring. By December 1995, the storage ring was recommissioned with the OK-4 undulators to produce tunable spontaneous radiations from infrared to ultraviolet. By the spring of 1996, routine storage ring operations were performed in several operation modes. In the meantime, an FEL cavity system was designed and constructed including a state-of-the-art optical feedback system to stabilize the mirrors [5].

In November 1996, two years after commissioning the storage ring, the OK-4 FEL lased in the wavelength range 345–413 nm establishing a U.S. record for the shortest wavelength FEL. Within a week of lasing and operating in two-bunch mode, the OK-4 system produced the first nearly monochromatic γ-rays (12.2 MeV) with close to 100% linear polarization using the Compton scattering scheme in the storage ring [6].

The availability of a large dynamic aperture has been the key to the success of the Duke FEL storage ring. In Section II, we present the achieved transverse and energy apertures. Several unusual but interesting beam phenomena, including large transverse multibunch excitations (Saturn Rings) and beam capture from outside the RF separatrix, are reported in Section III. In Section IV, we discuss the typical operation modes of the Duke FEL storage ring. Finally, we summarize the achieved storage ring lattice and electron beam parameters in Section V.

II. AVAILABLE APERTURES

The Duke storage ring has been designed with a large six-dimensional (6-D) dynamic aperture by implementing the second-order geometric aberration compensation scheme [1], [2]. The 6-D dynamic apertures with the OK-4 FEL switched on or off were calculated by tracking electrons with different momenta in realistic lattices with higher order multipole errors in quadrupoles, rms errors in dipole, quadrupole, and sextupole settings, and rms errors in magnet alignment. A closed-orbit correction was performed before tracking the electrons. The computed transverse dynamic aperture for the on-momentum electrons, $\epsilon_x \geq 60$ mm-mrad, and $\epsilon_y \geq 30$ mm-mrad from simulations, are larger than the physical apertures limited by vacuum chambers (56 mm-mrad and 16 mm-mrad in horizontal and vertical planes). The computed energy dynamic aperture, $\epsilon_E/E > \pm 5\%$ (at $\epsilon_E/E = \pm 5\%$, transverse apertures are 18 σ_x and 48 σ_y, for 10% vertical emittance coupling, where $\sigma_{x,y}$ are transverse Gaussian beam sizes), is larger than the energy acceptance determined by the existing RF system, e.g., $\pm 2.7\%$ at 1 GeV (maximum RF voltage of 650 kV). Therefore, the dynamic aperture should not be a limiting factor for the attainable aperture in such a system. Instead, the realizable 6-D aperture is determined mainly by the physical acceptance, the closed-orbit distortion, and the RF voltage. The success of the Duke storage ring commissioning and operation has proven that the available aperture is physically limited.

The first evidence of a large transverse aperture came from the success of stacking the injected electron beam into the buckets of the stored beam using one kicker. We were forced to adopt this one-kicker configuration for injection since the other two kickers had not been built due to budget constraints. With this configuration, both the stored beam and the injected beam were kicked to split the 4.8-mrad horizontal

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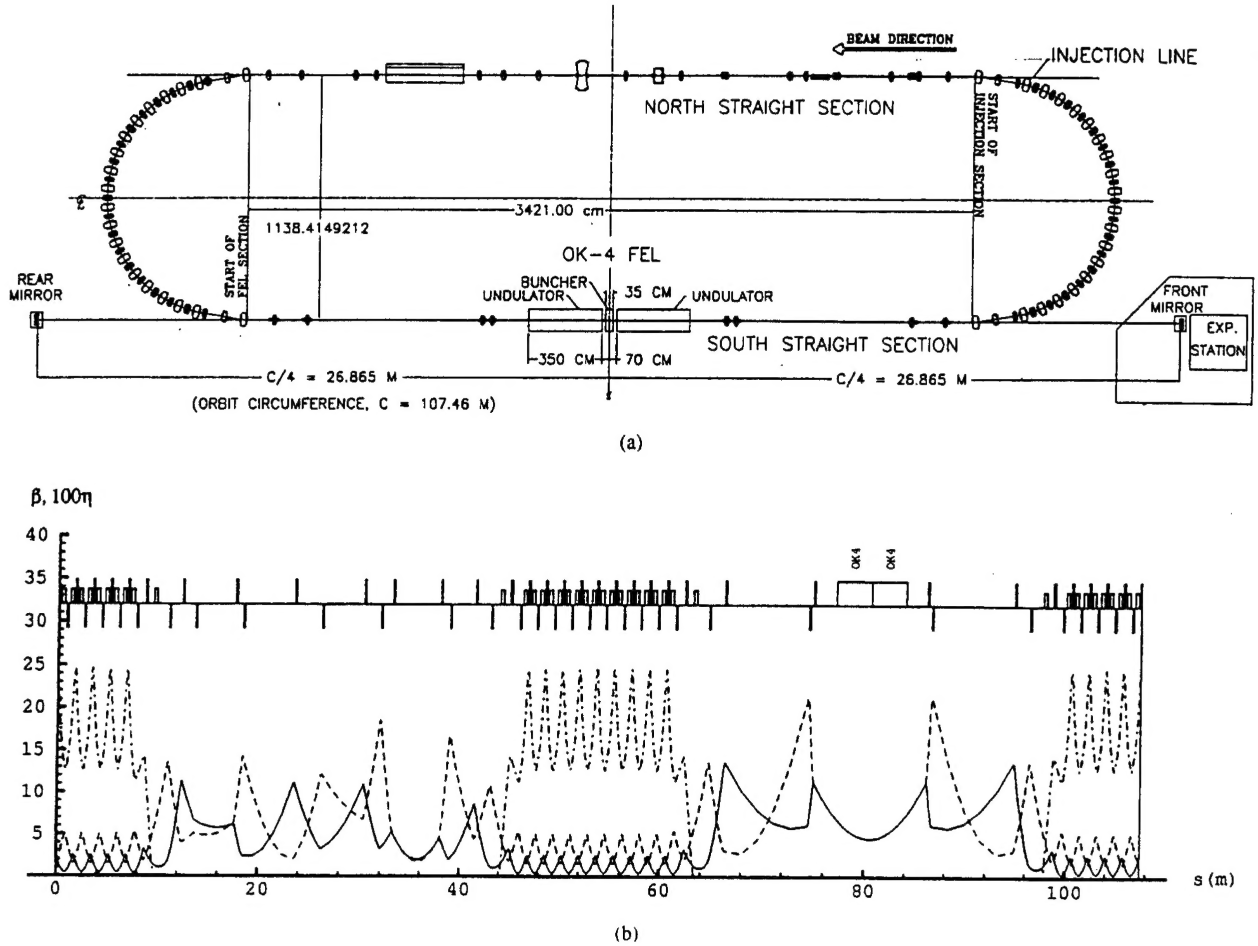

Fig. 1. The Duke FEL storage ring lattice with two long, straight sections: (a) lattice layout with OK-4 FEL located in the south straight section; (b) the designed β and η-functions with the OK-4 FEL turned off. The solid line is β_x, the dashed line is β_y, and the dot-dashed line is 100 η_x, all in meters.

angle of the injected beam at the location of the kicker ($\beta_x = 4.9$ m). Successful stacking indicates that the available horizontal aperture (A_x) must be larger than 28 mm-mrad [$A_x = (x')^2 \times \beta_x$ with $x' = 2.4$ mrad].

Available horizontal and vertical apertures can be measured using a calibrated kicker and a septum magnet, respectively [7]. At injection energy (230–285 MeV), the measured apertures are 43 mm-mrad (horizontal) and 7.5 mm-mrad (vertical). They are consistent with the size of the physical acceptance, provided that the closed-orbit distortion is taken into account.

The initial evidence of a large energy aperture came from the chromaticity measurements. The chromaticities were obtained by measuring the betatron tunes at different beam energies by varying the RF frequency. We were able to maintain a stored beam within a large range of RF frequencies (178.516–178.668 MHz). This range of RF frequencies corresponds to a relative energy deviation of ±5%, which indicated a large available energy aperture.

A train of micropulses separated by 350 ps are injected from the linac into the storage ring and captured by ring RF separatrices. By increasing RF energy acceptance, captured micropulses, while undergoing synchrotron oscillations, can be lost to the energy aperture if it becomes smaller than the RF energy acceptance. The energy aperture can be determined by measuring the loss of captured micropulses. At injection energy, the measured energy aperture was about ±3.3%. Taking into account energy aperture reduction due to orbit distortions in the arcs (±1.2%) as well as energy spread in the linac beam (±0.5%), the total energy dynamic aperture for an ideal beam would be about ±5%, which confirms our previous simulation results.

Large transverse and energy apertures not only made commissioning and operation of the Duke storage ring a success but also surprised us with several unusual phenomena including strong transverse multibunch excitations (Saturn rings) and electron capture from outside the RF separatrix.

III. Unusual Phenomena

One of the exciting things about the Duke storage ring is that we can operate it near some low-order betatron resonances. By using two families of sextupoles (in addition to two families of chromatic sextupoles) we were able to eliminate the horizontal second-order geometric aberration terms and at the same time reduce the coupled second-order geometric aberration terms [1], [2]. By doing so, we eliminated the horizontal third-order resonance and reduced the strength of the third-order coupled resonances. In addition, the fourth-order resonances are usually weak due to the absence of strong octupole terms and proper compensation of the fourth-order resonance terms in the FEL

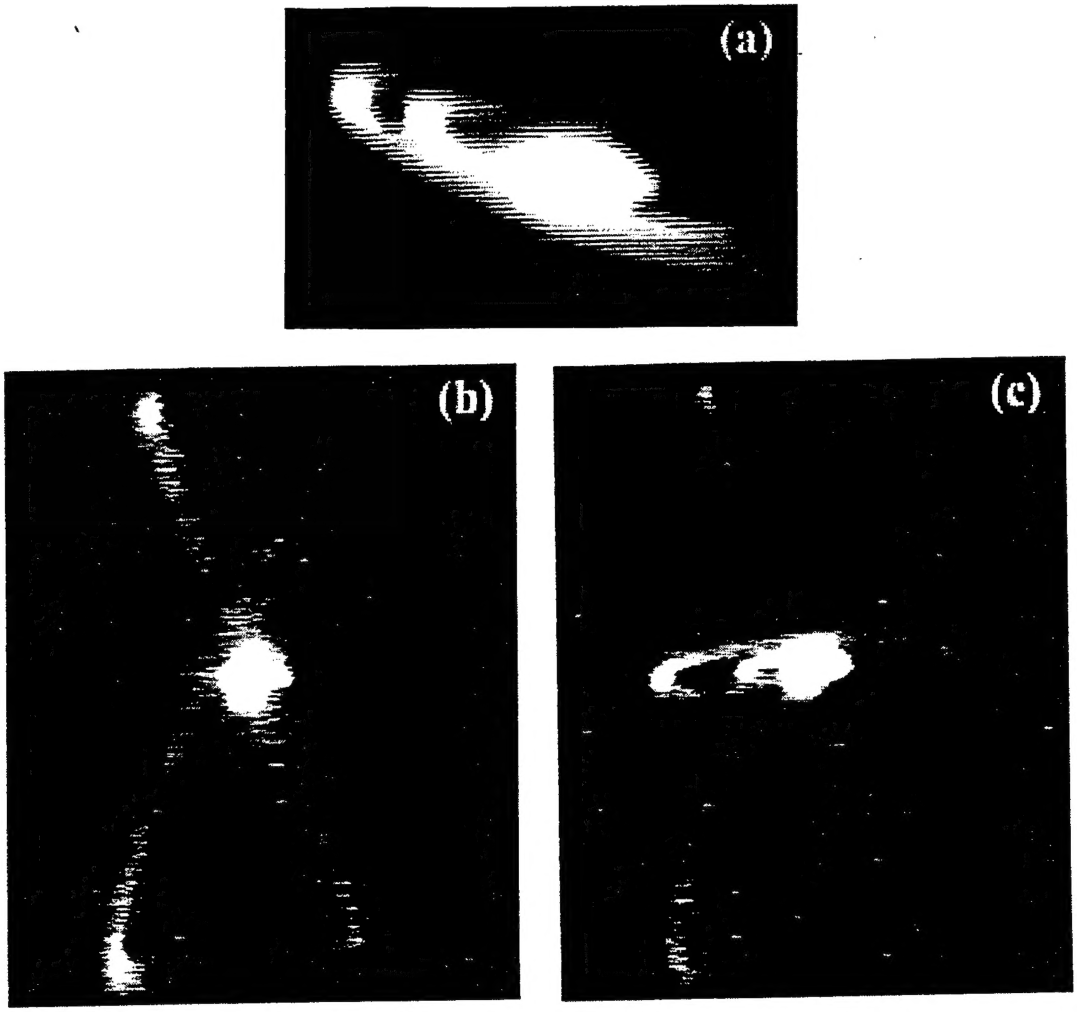

Fig. 2. Different Saturn ring patterns due to multibunch coherent oscillations: (a) mostly horizontal Saturn rings with a half-width $\max(\Delta x) = 3.6$ mm; (b) two rings due to coupled motion with dimensions $(\Delta x, \Delta y) = (2.0, 4.3)$ mm; (c) horizontal rings plus two coupled rings with dimensions $(\Delta x, \Delta y) = (2.4, 4.3)$ mm.

undulator. We were able to operate the storage ring near third- and fourth-order resonances without significant loss of beam current. For example we can tune the storage ring lattice across the vertical fourth-order resonance while maintaining the beam current.

Four stations were set up in each corner of the storage ring to provide basic beam diagnostics. Photomultiplier tubes, CCD cameras, and optical beam position monitors were installed at the stations to monitor the beam behavior using synchrotron radiation from corner dipoles. Very bright "Saturn" rings with well-defined patterns were first observed in April 1995 by the CCD cameras (Fig. 2). The Saturn rings occurred in the multibunch mode of operation while we were tuning the RF cavity using the higher-order harmonic tuners. Due to the orbit distortion, an off-axis bunch would excite higher-order transverse modes while passing through the RF cavity. These transverse modes in turn act upon other bunches to excite transverse instabilities. Saturated instabilities form Saturn rings which typically lasted for 5–20 s without significant loss of beam current.

At injection energy, the maximum measured dimensions of the Saturn rings were $\Delta x = 3.6$ mm (compared to the natural beam size $\sigma_x = 0.040$ mm) and $\Delta y = 4.3$ mm ($\sigma_y < 0.028$ mm) (Fig. 2). An estimate can be made for the lower boundaries of the transverse apertures using the Saturn ring dimensions which yield $\epsilon_x = 10.5$ mm-mrad and $\epsilon_y = 3.1$ mm-mrad ($\beta_x = 1.2$ m and $\beta_y = 6.1$ m). The Saturn rings were well contained within the available aperture (see Section II), therefore such huge transverse instabilities could be sustained; otherwise, substantial beam loss to the aperture would occur. Further studies will be carried out to identify transverse modes in the RF cavity which are responsible for such a phenomenon.

A very interesting beam capture phenomenon has also been observed: electrons can be captured even though they are initially injected outside the RF separatrices (Fig. 3). The energy of the injected beam can be mismatched with that of the stored beam causing electrons to be injected outside the RF separatrices of the storage ring. If the energy dynamic aperture of the storage ring is larger than the energy acceptance defined by the RF system, the electrons outside the separatrices would follow the equal-potential trajectories in phase space. Eventually, they are either lost by hitting the energy dynamic aperture or are captured through openings in the separatrices

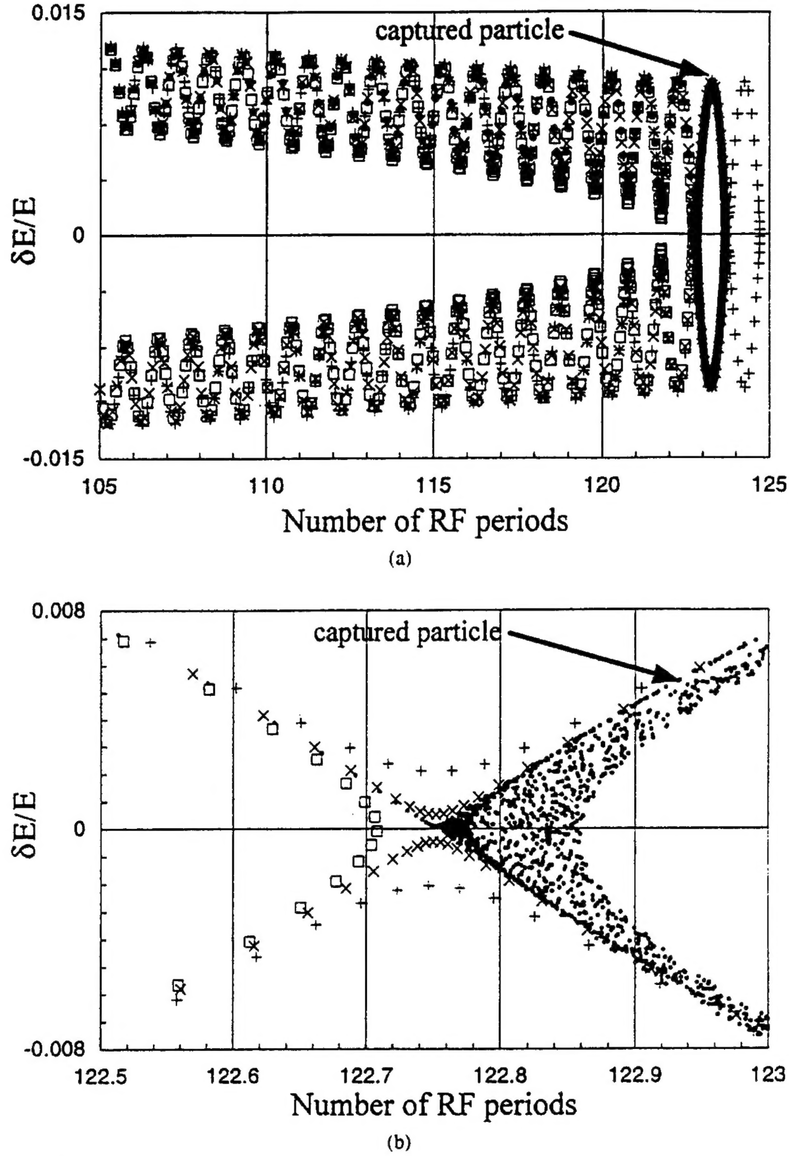

Fig. 3. Electrons injected outside of the RF separatrix but inside the dynamic energy aperture can be recaptured due to radiation damping and diffusion. Plots (a) and (b) show the tracking data from simulation for electron capturing at a storage ring energy of 271 MeV. The injected beam energy is 3% higher than the ring energy, and the RF separatrix has a $\pm 1\%$ energy acceptance. Each RF period corresponds to 5.6 ns. At the RF period number zero, four electrons are injected with initial energy deviations up to 3×10^{-1}. One of them is captured by the opening of the RF separatrix.

due to diffusion and radiation damping. A capture efficiency of about 20% was observed in our experiment. The captured electrons were somewhat evenly distributed in all 64 buckets in the storage ring, indicating that the captured electrons had undergone extensive longitudinal motion in phase space before being captured in a separatrix (Fig. 3). This phenomenon has directly proven that the energy dynamic aperture is larger than the RF energy acceptance of the experiment ($\pm 2\%$).

IV. Operation Modes

An Experimental Physics and Industrial Control Systems (EPICS)-based computer control system was developed for the Duke FEL storage ring [8] and continues to be improved to the present day. All ring magnets, dipoles, and combined function quadru-sextupoles are precisely controlled to provide proper magnetic fields by using the magnetic measurement data [10]. In addition, a high-level control system built above the EPICS control system has been developed to facilitate the routine operation of the storage ring by providing a set of essential control functions: magnet normalization, energy ramping, betatron tune and chromaticity tuning, and snapshot saving, modification, and restoration.

Typical operation of the Duke storage ring involves several important procedures such as system preparation, beam injection, energy ramping, and operation point tuning. During system preparation, all ring magnets are normalized by following the same standardization curves used during magnetic measurements. We use snapshots to record the previous settings of all ring systems, and they are very useful for recovering previous operation modes. Using the snapshot modification tool, a selected snapshot is usually adjusted for a particular injection energy before being used to restore all ring systems.

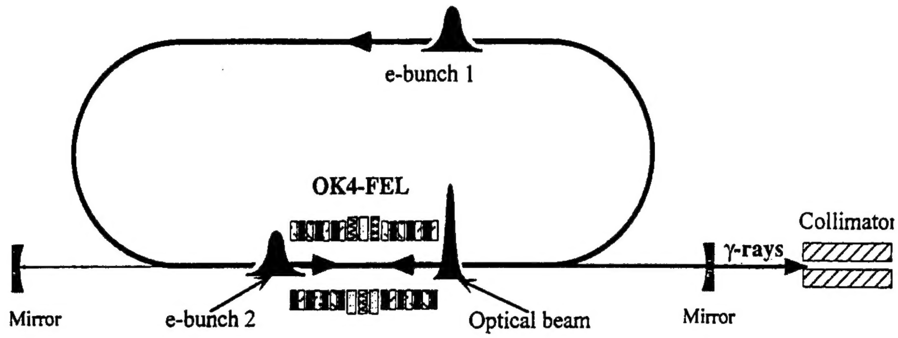

Fig. 4. Two-bunch mode operation of the Duke FEL storage ring for γ-ray production. The optical beam generated by the first electron bunch is bounced back to collide with the second electron bunch in the OK-4 FEL cavity to generate γ-rays.

The Duke FEL storage ring employs a linear accelerator (a linac) as its injector [11] and a thermionic RF gun as its electron source. The electron pulse can be generated by either thermionic emission or photon emission [12]. With thermionic emission, an electron pulse is chopped by a pulsed electrostatic kicker after the RF gun to about 50 ns with about 2–3 nC of charge. With photon-emission using a pulsed nitrogen laser, much shorter pulses (1–3 ns) can be generated with a typical current of 0.15 nC per pulse. The present linac delivers 230–285-MeV electron beams to the storage ring. The injected beam can be easily stored if a well-established snapshot for injection is used. Modifications in the linac-to-storage-ring transport are occasionally necessary to compensate for the angle and offset of the injected beam.

Energy ramping capability is essential for operating the storage ring at energies higher than the injection energy. The storage ring is ramped to its final set point by briefly stopping at several intermediate points. A high-energy set point is initially created by extrapolating the ring system settings from the injection energy snapshot and magnetic measurement data. To achieve better performance, fine tuning of the set point is sometimes necessary.

Operation point tuning is critical for optimizing storage ring operation. Using two tune knobs implemented in the two straight sections and a chromaticity knob implemented in the arcs, we can change the lattice tunes and chromaticities. Each knob controls a certain group of quadrupoles in the storage ring. By changing betatron tunes, we can reduce the lattice sensitivity to orbit errors and avoid beam loss due to strong resonances. Chromaticity tuning allows us to maximize the peak current by suppressing the head–tail instability of the beam. Because the second-order geometric aberration compensation implemented in the Duke storage ring is localized, the betatron tune changes in the straight sections do not reduce the optimized dynamic aperture [9]. In addition, several local orbit bump knobs have been developed to facilitate alignment of the electron beam with the optical axis of OK-4 FEL cavity. With these local bumps, we were able to optimize the operation of the OK-4 FEL laser and γ-ray source.

Several different bunch modes of operation have been established which optimize the storage ring to operate as a synchrotron light source, an FEL laser, and a γ-ray source. Multibunch operation mode is suited for synchrotron radiation applications where a large average current is preferred. By shifting the kicker timing, we can fill part or all of the 64 buckets of the storage ring. A maximum current of about 155 mA was stored in this multibunch mode of operation at injection energy.

Single-bunch mode operation with a high peak current to maximize the FEL gain is desirable for FEL operation. Operating in this mode, the OK-4 FEL system first lased in November 1996 in the wavelength range of 345–413 nm. Using energy ramping, the OK-4 FEL has achieved lasing at several energies: 273, 400, 500, and 550 MeV.

A two-bunch mode of operation is designed for the Duke FEL storage ring to operate as a γ-ray source [6] (Fig. 4). In this mode, two electron bunches separated by half of the storage ring circumference are stored in the ring. Either one or both of the bunches can lase in the OK-4 system. The lasing optical pulse generated by one electron bunch collides with the second electron bunch producing high-energy photons, the γ-rays. Operating the storage ring in two-bunch mode at 500 MeV, the first nearly monochromatic γ-rays at 12.2 MeV, with an energy resolution of about 1% full-width at half-maximum (FWHM) and close to 100% linear polarization, were produced within a week of the initial OK-4 FEL lasing. Due to a large energy acceptance limited by the RF (3% at 500 MeV), the scattered electrons were not lost while producing γ-rays. However, a loss mode γ-ray operation is expected when the energy loss of the electron beam exceeds the energy acceptance of the storage ring system.

V. Measured Performance

Two types of parameters are important to the performance of the storage ring: the lattice parameters and the electron beam parameters. Important lattice parameters include betatron tunes, chromaticities, synchrotron tune, β-function, η-function, closed-orbit, single particle dynamic aperture, and impedances of vacuum chambers. Important electron beam parameters include the beam emittance, bunch length, energy spread, beam lifetime, and maximum stored beam current.

The measured parameters of the Duke storage ring are summarized in Table I. Most of the lattice parameters are measured at the injection energy. Measurements at higher energies usually yielded similar results. Besides a large dynamic aperture (Section II), the measured circumference, betatron tunes, and chromaticities agreed very well with the design values.

TABLE I
MEASURED DUKE FEL STORAGE RING PARAMETERS AT VARIOUS ENERGIES AS INDICATED

Storage ring parameter	Measurement (260-285 MeV)	Design (1 GeV)
Operation energy (GeV)	0.23-1.1	0.25-1.0
Circumference (m)	107.453	107.455
Operational Tunes: Q_x, Q_y	9.290, 4.260	9.1107,4.1796
Chromaticities: ξ_x, ξ_y	0.26, 0.17	+0, +0
Orbit distortions ΔX, ΔY (mm)	$< \pm 5$, $< \pm 4$	
β functions: $\Delta\beta_x/\beta_x$, $\Delta\beta_y/\beta_y$	$< \pm 20\%$, $< \pm 20\%$	
η function in straight section (mm)	< 5	0
Apertures	Measured	Dynamic
Horizontal, Vertical (mm-mrad)	43, 7.5	60, 30
Energy	$> 3.3\%$	$> 5\%$
Current (multi-bunch) (mA)	155	100 (initial) 1000 (final)
Current (one-bunch) (mA)	8	40
Current (two-bunch) (mA)	10.8 (5.4 mA each)	
Lifetime (one-bunch) (hour)	about 3 (8 mA)	
	Measurement (500 MeV)	
Current (two-bunch) (mA)	8.6 (4.3 mA each)	
Bunch length(one-bunch) σ_s (ps)	70 (8 mA, 500 kV RF)	
	Measurement (1 GeV)	
Emittances (nm-rad)	17 ± 2, $\epsilon_y < 1$	18, $\epsilon_y < 0.2\epsilon_x$

The storage ring is usually operated with higher fractional betatron tune values in order to reduce the sensitivity to orbit distortions. The measured synchrotron tunes are usually within $\pm 5\%$ of the calculated values for a given RF voltage. The measured β functions in the center of the quadrupole magnets differ from the design values by less than $\pm 20\%$. Residual η-functions in the straight sections are small (<5 mm) and closed-orbit distortions are less than ± 5 mm in transverse planes even without the use of correctors.

The electron beam emittance was measured at 1 GeV by analyzing a video image of the beam captured from a diagnostic CCD camera. The measured emittance, 17 ± 2 nm-rad in the horizontal plane, agreed very well with the design value of 18 nm-rad. The vertical emittance (<1 nm-rad) was estimated from the diffraction limited vertical beam size.

The bunch length was initially measured using a dissector manufactured in Russia at the Budker Institute of Nuclear Physics. Recently, through cooperation with the APS diagnostic group, we were able to measure both the electron bunch length and profile as a function of storage ring current and RF voltage using a streak camera. The measurement results will be published elsewhere. A typical measured bunch length of an 8-mA beam in single bunch mode was $\sigma_s = 70$ ps at 500 MeV and 500 kV RF voltage, while the unlengthened bunch length is about 16 ps at very low current (<0.1 mA). Using these results, we estimated the vacuum chamber longitudinal impedance of the Duke storage ring was 2.75 Ω.

The typical vacuum readings in the Duke FEL storage ring range from 10^{-10} to 10^{-9} torr without e-beam. With a stored beam, the vacuum in the arcs usually increases by a factor of ten while increasing only slightly in the straight sections. No substantial ion-trapping has been observed since the first stored beam. The electron beam lifetime is mainly limited by residual gas scattering and Touschek effects. At the injection energy, the typical $1/e$ lifetime for an 8-mA beam is about 3 h. A measured beam lifetime at 500 MeV is about 2.2 h at 3.7 mA independent of OK-4 lasing status and γ-ray production. In general, the OK-4 lasing and γ-ray production in no-loss mode does not affect the beam lifetime.

VI. CONCLUSION AND FUTURE DEVELOPMENT

The Duke FEL storage ring has been in operation for more than two years. During this period we have achieved and surpassed the initial goals of operating at 1 GeV and storing 100 mA at injection energy. We also confirmed a large 6-D aperture and measured a number of important lattice and beam parameters. With the OK-4 FEL lasing and the production of monochromatic γ-rays in November 1996, we have established several modes of operation optimized for synchrotron radiation, FEL, and γ-ray applications.

In order to achieve reliable injection, a timing jitter of several nanoseconds over a period of a few minutes in the current photocathode injection system must be reduced to a level of less than 1 ns. To allow future loss mode operation of

γ-ray production, a better injection system which is capable of delivering up to 5 nC per pulse with a pulse length shorter than 5 ns must be developed. Thermionic emission with an optimized gun kicker operation is under consideration. The preliminary data indicate that the existing gun kicker is capable of producing 5-ns pulses, provided that the injection lattice is properly matched.

To improve injection efficiency and operate in a high-current mode at the nominal energy (1 GeV), a full injection system with three kickers will soon be commissioned and specially designed arc crotch chambers with water cooled absorbers will be installed to handle a high-radiation heat load from increased synchrotron power output. To achieve more reliable operation from the storage ring, the BPM electronics will be installed and commissioned, and an orbit correction and feedback system will be developed.

In the future, we plan to spend more time studying the interesting beam phenomena observed during initial operation. In addition, we are looking forward to attempting OK-4 lasing at record-breaking wavelengths. Operating at various energies and FEL wavelengths, we will also try to produce tunable γ-rays with a wide range of energies from 1 to 225 MeV.

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REFERENCES

[1] Y. Wu *et al.*, *Nucl. Instrum. Methods*, vol. A331, pp. 287–292, 1993.
[2] Y. Wu *et al.*, *Nucl. Instrum. Methods*, vol. A341, pp. 363–366, 1994.
[3] V. N. Litvinenko *et al.*, in *Proc. Particle Accelerator Conf.*, Dallas, TX, 1995, pp. 213–215.
[4] I. B. Drobyazko *et al.*, *Nucl. Instrum. Methods*, vol. A282, p. 424, 1989.
[5] I. Pinayev, private communication.
[6] V. N. Litvinenko *et al.*, *Phys. Rev. Lett.*, vol. 78, no. 24, pp. 4569–4572, June 1997.
[7] Y. Wu *et al.*, in *Proc. Particle Accelerator Conf.*, Dallas, TX, 1995, pp. 2877–2879.
[8] Y. Wu *et al.*, in *Proc. Particle Accelerator Conf.*, Dallas, TX, 1995, pp. 2214–2216.
[9] Y. Wu, Ph.D. dissertation, Duke Univ., Aug. 1995.
[10] B. Burnham *et al.*, in *Proc. Particle Accelerator Conf.*, Dallas, TX, 1995, pp. 524–526.
[11] P. G. O'Shea *et al.*, in *Proc. Particle Accelerator Conf.*, Dallas, TX, 1995, pp. 1090–1092.
[12] P. G. O'Shea *et al.*, private communication.

Invited Paper

First UV/visible lasing with the OK-4/Duke storage ring FEL: design and initial performance

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ABSTRACT

The OK-4/Duke storage ring FEL was commissioned in November, 1996 and demonstrated lasing in the near UV and visible ranges (345-413 nm). The OK-4 is the first storage ring FEL with the shortest wavelength and highest power for UV FELs operating in the United States. During one month of operation we have performed preliminary measurements of the main parameters of the OK-4 FEL: its gain, lasing power and temporal structure. In addition to lasing, the OK-4/Duke FEL generated a nearly monochromatic (1% FWHM) 12.2 MeV γ-ray beam [1]. In this paper we describe the design and initial performance of the OK-4 /Duke storage ring FEL. We compare our predictions with lasing results. Our attempt to lase in the deep UV range (around 193 nm) is discussed. The OK-4 diagnostic systems and performance of its optical cavity are briefly described.

2. INTRODUCTION

The OK-4 /Duke storage ring FEL project is a collaboration of the Duke University Free Electron Laser Laboratory and the Budker Institute of Nuclear Physics established in 1992 [2]. The OK-4 FEL was built and operated in the 240-690 nm range using the VEPP-3 storage ring at Novosibirsk [3]. After commissioning the 1.1 GeV Duke storage ring in November, 1994 [4], the OK-4 FEL made a trip around the globe and came to Duke in May, 1995. It was installed on the Duke storage ring in November of the same year. Modifications of the Duke storage ring vacuum system for the OK-4 FEL and 54-meter long optical cavity were completed by August, 1996. A sophisticated feed-back and control system of optical cavity mirrors was later commissioned. Main part of the OK-4/Duke XUV FEL design, construction and installation team are shown in Fig.1. This photograph was made in front of the OK-4 on August 2, 1996, just one day before the installation of the shielding blocks and the start of OK-4 commissioning.

In August, 1996 commissioning of the OK-4 FEL with its optical cavity was initiated at a wavelength of 193 nm using a temporary power supply for the OK-4 buncher. The results of these runs were inconclusive because of strong ripples in this temporary supply. In addition, the mirror holder clamps were too strong reducing the radius of curvature of the mirrors and making the optical cavity unstable as shown by direct measurement in October, 1996. During the period September-October, 1996, power supplies for the OK-4 wigglers and buncher were brought close to specifications and a new set of mirrors with a central wavelength of 380 nm was installed for the first demonstration experiment. We have used a

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different clamping technique to avoid mirror distortions. An UV streak-camera was brought to Duke from APS (Argonne National Laboratory) and has been used to measure electron bunch length, optical cavity length and FEL pulse length.

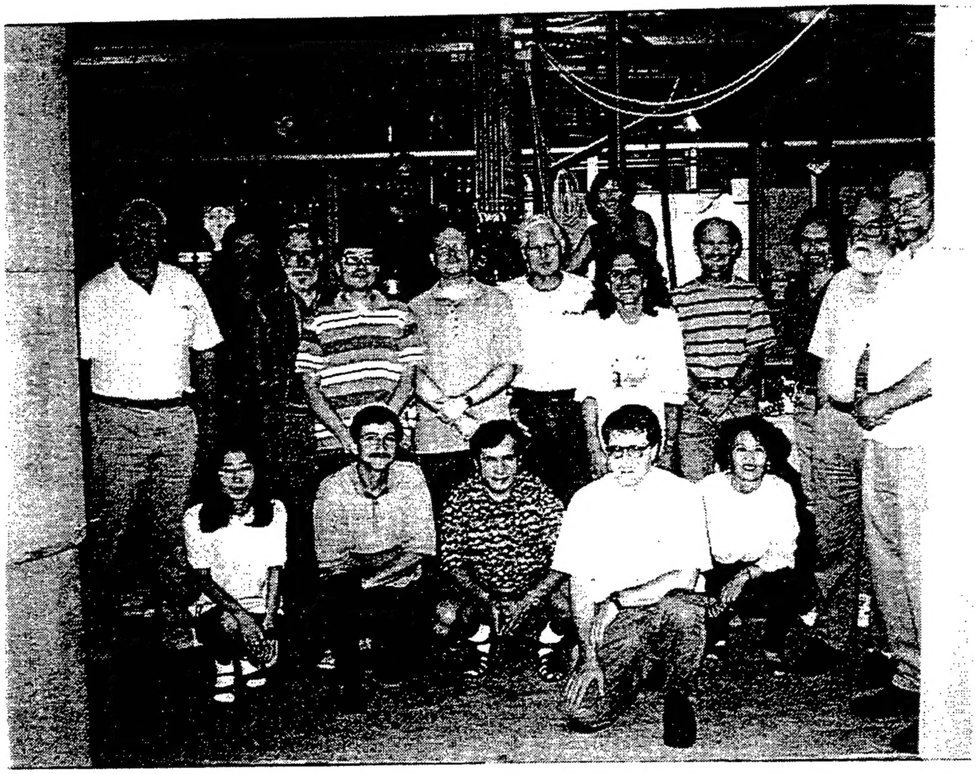

Fig. 1. Members of the OK-4/Duke XUV FEL design, construction and installation team at Duke (left to right, front to back): S.H.Park, M. Emamian, I.V.Pinayev, S.Goetz, P.Wang, P.Morcombe, H.Goehring, O.Oakeley, Y.Wu, B.Burnham, G.Detweiler, V.N.Litvinenko, C.Kornegay, N.Hower, J.Meyer, G.Swift, J.Faircloth and J.Patterson.

The very first OK-4 operation on November 13, 1996, was successful. The OK-4/Duke storage ring FEL demonstrated operation in the near UV/visible range with a tunability of ±18% around the center wavelength of 380 nm. Lasing was demonstrated at injection energy (267.5 MeV) and other operational energies (400 - 550 MeV) which were within the tunability range of the OK-4 wigglers and their power supply. The main problem was the "blind-folded" alignment of the electron beam with the optical cavity in the absence of beam position monitors (BPM). The high gain of the OK-4 FEL (>9% per pass at 3.5 mA/bunch) and low cavity losses (0.6% per pass at 380 nm) helped to solve this problem. We have used our OK-4 diagnostics and lasing for both electron and laser beam alignment. Two days later, using two 500 MeV electron bunches separated by one half of the storage ring circumference and lasing at 380 nm, we demonstrated the generation of 12.2 MeV γ-rays via intracavity Compton backscattering [1]. We demonstrated tunability of the γ-ray energy (up to 15 MeV) by tuning the laser wavelength and/or the energy of the electron beam. We conducted the study and measurements of the main parameters of the OK-4 FEL in parallel with these experiments. After one month of operation, which was mostly dedicated to γ-ray generation and spectrum measurements, the injector for the storage ring was shut down to condition one of the klystrons. We expect to resume operation of the OK-4 FEL when conditioning is finished.

In Chapter 3 we present a description of the OK-4 FEL and the Duke storage ring. Chapter 4 gives a brief description of the OK-4 optical cavity and diagnostics. OK-4 FEL commissioning and results are described in Chapter 5. Chapter 6 contains conclusions and discussions of future plans for the OK-4/Duke XUV FEL.

3. THE OK-4/DUKE XUV STORAGE FEL

3.1 Duke storage ring

The Duke 1.1 GeV storage ring has a 34 meter long straight section dedicated for FEL operation. The present lattice has both transverse β-functions of 4 meters at the center of the OK-4 to optimize the gain. The storage ring RF system [5] operates at 178.5 MHz (64th harmonic of the revolution frequency) and can support up to 64 electron bunches. In multibunch mode (two or more bunches) we have used high order mode (HOM) tuners to suppress or reduce multi-bunch instability. The RF system has computer controlled low level electronics. The 150 kW RF cavity has two main and two HOM tuners with a 50 kW transmitter. The transmitter power limits the maximum accelerating voltage to 600 kV. Typical OK-4 FEL operation mode used RF voltage upto 550 kV. The storage ring is equipped with 54 beam-position monitors (BPM) but none of the BPM electronics are available. To operate the OK-4 FEL, we were forced to develop very complicated and labor-intensive methods to measure the orbit [4]. A set of local compensated bumps was used to align the electron beam in the OK-4 FEL. Orbit corrections took a substantial part of the time allocated for commissioning. We are planning to test two types of BPM electronics in the near future and equip the ring with the best units.

Table I. Recent Duke Storage Ring Electron Beam Parameters

Operational Energy [GeV]		0.25-1.1
Circumference [m]		107.46
Impedance of the ring, Z/n, [Ω]		2.75±0.25
Stored current [mA][a]		
multibunch		155
single bunch		20[b] /8[c]
Bunch length, σ_S[ps][d]		
natural (low current)		15
with 5 mA in single bunch		60
Relative Energy spread, σE/E [d]		
natural (low current)		$2.9 \cdot 10^{-4}$
at 5 mA in single bunch		$1.1 \cdot 10^{-3}$
Peak Current [A] [d]		
with 5 mA in single bunch		12
with 20 mA in single bunch [e]		31
Horizontal Emittance [nm*rad]		
5 mA/ bunch @ 700 MeV	< 10[f]	
3 mA/ bunch @ 500 MeV	< 8 [f]	

[a] Maximum current at 1 GeV is limited to 2-3 mA before crotch-chambers with absorbers are installed; [b] Per bunch using standard mode of multibunch injection from the 270 MeV linac; [c] In single injection mode with 1 nsec photocathode gun; [d] At 500 MeV, V_{RF}=500 kV; measured by the streak-camera [9] and dissector; [e] Expected from broad band impedance model with Z/n = 2.75 Ω; [f] Extracted as the top limit from the OK-4 spontaneous radiation spectra.

The existing linac-injector with maximum energy ~270 MeV was operating in photo-injector mode for these experiments [6]. Preparation of the linac for injection took most of our operational time (usually from 9 a.m. until 4-6 p.m.) leaving late evenings for the OK-4 and γ-ray shifts. Other problems were associated with the use of a single kicker for injection and low charge per bunch (0.1 nC, i.e 0.3 mA per shot) from the linac-injector operating in photocathode mode [6] limiting the maximum stored current to 8 mA/bunch. Photocathode operation required additional thermal heating of the cathode providing background thermionic emission in 10-15 buckets. We have also observed time drift of the injection pulses as large as 5 nsec, which must be investigated. Previous injection mode utilized a pulsed gun-kicker providing ~25-50 nsec

long train of electron bunches but with substantially higher charge per RF bucket. We are planning to use this injection mode and a resonant kick-off system to store larger currents. We also plan to install two additional kickers to improve efficiency of injection. The main parameters of the low emittance Duke storage ring are published elsewhere [4,7]. An update of the parameters is summarized in Table I. Main parameters have been measured using a number of different techniques and are in good agreement with one another.

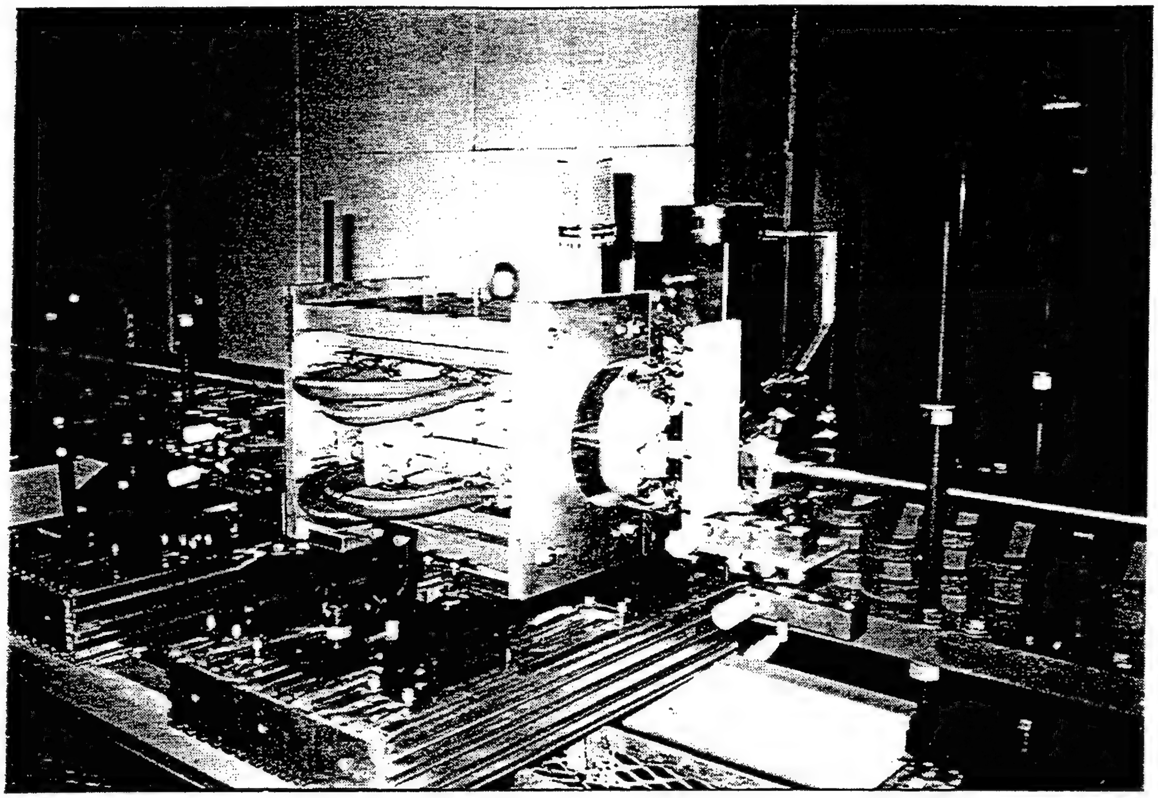

Fig.2. Two electro-magnetic wigglers and the buncher of the OK-4 FEL during installation in the South straight section of the Duke storage ring (October, 1995). The OK-4 buncher (at the center) and vacuum system are fully assembled. The wigglers have their tops off and expose details of the design: the wiggler yoke, the coils and the flat vacuum chambers.

3.2 OK-4 FEL

The main parameters and expected performance of the OK-4 FEL are described in previous publications [3,8]. Table II gives an up-to-date summary of the parameters. Fig. 2 shows the OK-4 magnetic system, comprising two electromagnetic wigglers and a buncher, in the process of installation on the ring. The magnetic system of the OK-4 FEL was slightly modified for installation on the Duke storage ring. The gap in the OK-4 was increased to 2.25 cm to accommodate a new vacuum chamber. The buncher was shifted from the center of the OK-4 to provide a free from magnetic field collision point for the Compton γ-ray source. The 11 meter long vacuum chamber has 8 meters of constant cross-section and two 1.4 m long smooth transitions from the 2.2 cm x 7.5 cm flat shape to the 10 cm round pipe. Three ion pumps are located at the center and both ends of the system, providing vacuum pressures in the 10^{-10} torr range.

Two Trans-Rex (5 kA, 500 V) power supplies were donated to Duke by Fermi Lab and were in poor condition. They have been repaired, equipped with large external LC filters and are presently used to drive the OK-4 wigglers and buncher. During the August, 1996 runs only one Trans-Rex was operational and we used an old power supply for the buncher. This power supply had ripples ~2-3% and was the main obstacle to achieve lasing at 193 nm. In November, 1996 both Trans-Rex power supplies were operational.

Nevertheless, the wigglers' power supply had a current limitation at 2.1 kA which limited the maximum energy electron beam we could lase with at 380 nm. Recently, the wigglers' power supply was tested at the design value of the OK-4 wigglers (3 kA). This provides for full 16-fold wavelength tunability of the OK-4 fundamental hammonic. Overall performance of the OK-4 power supplies is close to specifications (50 ppm DC and ripples) and will be improved in the near future using a second stage of regulation and feedback. The OK-4 wigglers have a set of trim coils which are not used due to the excellent quality of the wigglers' magnetic field. The buncher (a three pole electromagnetic wiggler) is slightly miscompensated and its trim coil has been used. The controls of the OK-4 power supplies are part of the Duke storage ring computer control system [10]. This system provides flexible operation of the OK-4 and the possibility to ramp the energy of the storage ring without changing the OK-4 wavelength. A number of lattices (snapshots in control system terminology) were created to operate the OK-4 FEL at injection energy and also at 400, 500, 550, 600, 700 and 750 MeV. Once established, the snapshot can be used to re-establish lasing.

Table II. The OK-4 FEL Parameters

Optical cavity		
	Optical cavity length [m]	53.73
	Radius of the mirrors [m]	27.27 [a]
	Rayleigh Range in OK-4 center [m]	3.3
	Angular control accuracy [rad]	better than 10^{-7}
OK-4 wiggler [3,8]		
	Period [cm]	10
	Number of periods	2 x 33.5
	Gap [cm]	2.25 [b]
	Kw/I [1/kA] measured	1.804
	Kw	0-5.4

[a] Measured; [b] Increased to accommodate new vacuum chamber.

The RF-smooth crotch chambers providing passage of the optical beam have been designed but are still in the process of manufacturing. In order to facilitate commissioning of the OK-4 system, we have installed temporary crotches *without absorbers*. Non-smooth transitions keep impedance of the vacuum chamber rather large causing microwave bunch-lengthening to begin at ~0.1 mA per bunch at 500 MeV and is the main factor limiting the OK-4 gain. We have used a dissector with 15 psec resolution [11], the APS streak-camera, and spontaneous radiation spectrum measurements from the OK-4 to determine parameters of the electron beam in single bunch mode (Table I). According to the bunch-length and the OK-4 FEL gain measurements, the impedance of the vacuum chamber is ~2.75 Ohm. Detailed analysis of these measurements will be published separately.

4. THE OK-4 FEL OPTICAL CAVITY AND DIAGNOSTICS

The length of the OK-4 two mirror optical cavity is equal to one half of the ring circumference. The optical cavity mirrors are designed to have radii of 27.46 m and 4 m Rayleigh range at the OK-4 center to optimize the gain. The mirror substrates from UV grade fused silica were custom made by Lumonics Optics Group (Canada). Two sets of multi-layer dielectric mirrors with central wavelengths at 193 nm and 380 nm were manufactured. The 193 nm mirrors were used for the August, 1996 runs and the 380 nm mirrors for the November, 1996 runs. At our request, the 380 nm mirrors have a top layer of HfO to make the mirrors radiation resistant [3]. The strong absorption of HfO at 193 nm does not allow its use for protection of these mirrors.

The measured radii of the free-standing mirrors are shown in Table II and are within specified limits. The optical cavity is very close to the edge of stability and is extremely sensitive to angular misalignment of the mirrors. Deviations of the mirrors' angular position are amplified by a factor of 60 and translated into the

angle of the optical axis. In addition, the cavity has very tight tolerance on the radii of the mirrors which can be modified by thermal and mechanical stresses. Details of the stability analysis and thermal effects on the cavity parameters will be published elsewhere [12]. Fig. 3 shows an 8.3 m long downstream part of the optical cavity vacuum system and the mirror support and alignment system (built in Novosibirsk and modified at Duke) installed on an optical table. After a careful study of the vibration and angular motions of the table and optical cavity mirrors we found them unacceptably large. We cut a slab out of the concrete floor around the perimeter of the table to reduce the vibrations and found substantial improvement. Nevertheless, effects of personnel and equipment movement in the laboratory provided an unacceptable level of vibration and angular displacements. To solve this problem we have built a new mirror adjustment system using a unique unit combining both feedback and controls. The system provides 100-150 Hz feedback bandwidth and 40 nanoradian accuracy of control with 100 nanoradian long-term stability of the angular position of the mirrors without backlash [11]. Typical angular vibrations of the OK-4 mirror on a very quiet evening (with no personnel or equipment moving in the laboratory) with and without the feedback system are shown of Fig.4.

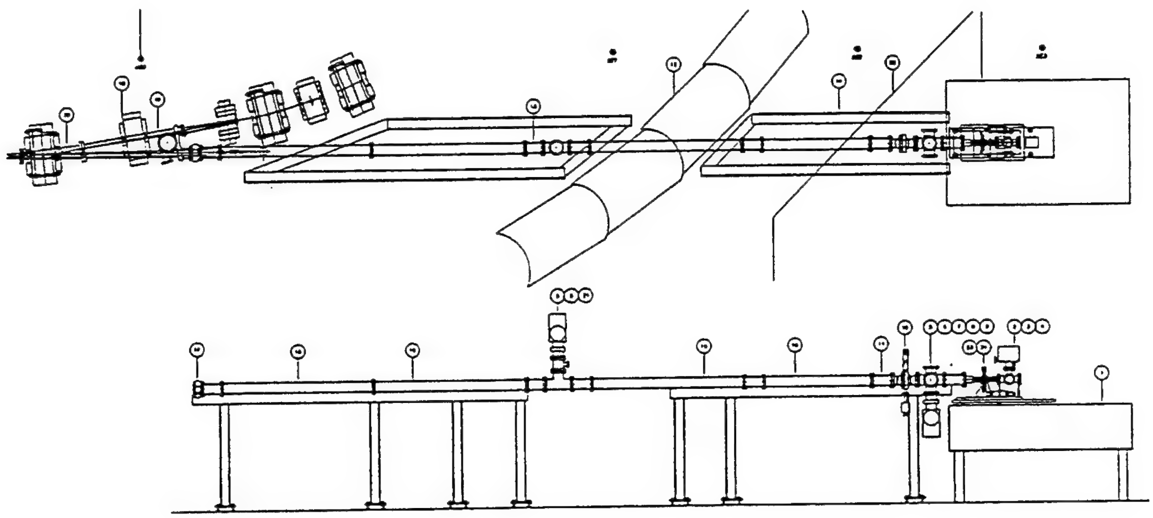

Fig. 3. Layout of the downstream wing of the OK-4 FEL optical cavity. The UHV chamber of the optical cavity penetrates the storage ring shielding and connects with the mirror system. The mirror system is installed on the 6x8 honeycomb optical table. The optical table is anchored to the concrete slab which is cut off from the main floor to reduce the level of vibrations. A similar design is employed for the upstream cavity. The vacuum chamber is terminated by 5 mm thick CaF windows at both ends. A remotely controlled periscope mirror is installed in front of the downstream mirror protecting it from undesirable exposure during storage ring tune-ups, and is used to extract spontaneous radiation from the OK-4 system through an additional CaF window.

The basic diagnostic system brought from BINP [3] together with the APS streak camera were heavily utilized during commissioning of the OK-4. The diagnostics incorporate the following [11]:

- A two port UV computer controlled monochromator equipped with an UV photomultiplier, CCD arrays, phosphor screens and video camera;
- CAMAC based precise 20-bit ADCs for tuning and spectrum measurements;
- Five CAMAC based 10-bit and 8-bit ADCs for fast measurements;
- EG&G 5202 Lock-in amplifier for optical cavity losses and length measurements;
- Mirror radii measurement system [12];
- Optical cavity feedback and control system [11];
- A stroboscopic dissector with 15 psec resolution;
- Six photon position monitors for orbit and tunes measurements and cavity control;
- Two He-Ne laser system with beam expanders for pre-alignment ;

- ❑ Two telescopes with autocollimation;
- ❑ Two vacuum gauges to monitor the vacuum near the mirrors.

During August, 1996 we found that the optical cavity exhibited behavior similar to an unstable one. We have used the precision (±5 cm for 30 m radius of curvature) mirror radius measurement system to measure the distortion caused by the stress from the mirror clamping/cooling device [12]. We found that distortions were asymmetric and caused a reduction of the radius of curvature below the stability threshold (R_c = 26.865 m for our cavity). We have used spring fingers to hold the 380 nm mirrors in the supports and did not observed any problems. High power and high energy operation of the OK-4 will require an efficient way to evacuate the heat generated in the mirror by spontaneous radiation. We are developing different options, including an all metal front mirror, metal turning flats and/or different types of clamps and UHV cooling techniques.

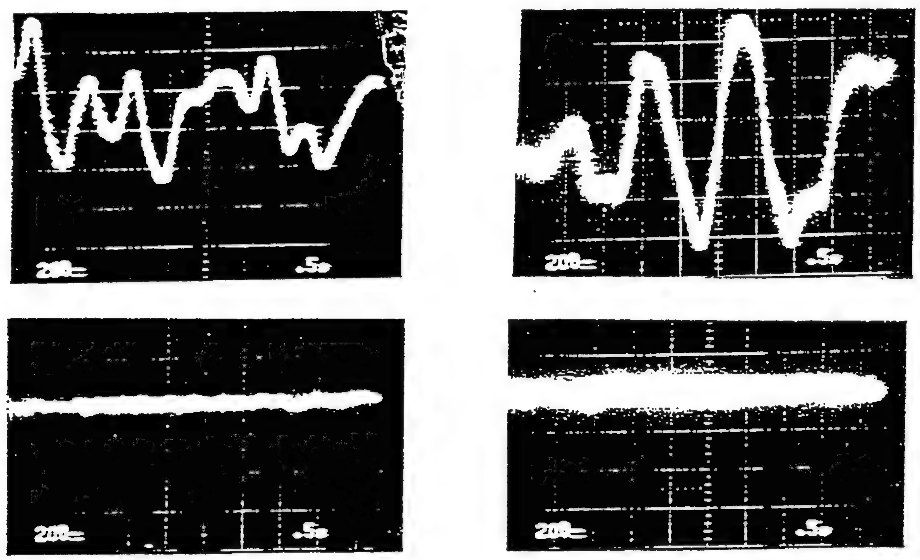

Fig. 4. The typical angular vibration of the optical cavity mirror measured with feedback off (top oscillograms) and on (bottom oscillograms) very late at night with no personnel or equipment moving in the laboratory. The angular position of the mirror was measured by an independent photon beam position monitor with a sensitivity of 24.8 mV/microradian. Without feedback, the mirror exhibited peak-to-peak angular vibration ~30 μrad in the horizontal plane and ~50 μrad in the vertical plane. In addition, a slow long term drift of the slab provided ~100-200 μrad per hour in both directions. Movement of a person in the vicinity of the optical table, or a car passing by outside the building, produced 3-5 times larger oscillations. With feedback on, residual vibrations were at the level of ± .04 μrad, and very high feedback DC gain (~10^4) provided for long term stability at the level of ± .1 μrad.

We have used a UV monochromator to measure spectra of the OK-4 spontaneous radiation. Measuring the spectra at different buncher settings one can determine the energy spread and estimate the emittance of the electron beam [3]. The results of this analysis are shown in Table I. Direct bunch length measurements with a dissector and streak camera were consistent with results extracted from the spectrum measurements. We did not observe diagnostic problems while operating above 200 nm. Operating below 200 nm we observed numerous oxygen and water absorption lines [4]. We plan to install a transport line purged with dry N_2 for operation below 200 nm. During the lasing attempt at 193 nm we used a second port of the monochromator equipped with a phosphor screen and a CCD video camera. We tuned the monochromator to 193 nm and recorded video images of the spectra using a VCR. This was our best attempt at laser observation with the unstable buncher power supply. In November, 1996 we did not have any problems using time averaged diagnostics.

5. COMMISSIONING OF OK-4/DUKE STORAGE RING FEL

We have established three main storage ring modes to operate the OK-4 FEL: injection energy of 260-270 MeV, 0.5 GeV and 0.7 GeV and a number of supplementary modes (350, 400, 550, 600, 650 and 750 MeV). We have measured β-functions in the OK-4 FEL and created computer tools to vary OK-4 wiggler current while keeping betatron tunes stable.

5.1. Lasing Attempt at 193 nm - August 1996.

On August 20, we ramped a single 6.5 mA bunch to 500 MeV and attempted to lase. The electron beam and optical cavity were pre-aligned using the technique described in [11]. We varied the RF frequency in the range ±0.043% (a circumference variation of ±4.6 cm) to synchronize revolution times of the optical and electron bunches. This range is substantially larger than the possible error in the length of the optical cavity. Ripples in the buncher power supply did not allow us to use time averaging diagnostics to study spectrum modifications due to the gain. We used a video system to record the spectra images at the phosphor screen. Each video frame contained a spectrum which is averaged over sampling time and is different from the instantaneous value. We have observed strong evidence of the amplification of spontaneous radiation correlated with peak current and detuning from synchronism. Fig.5 shows a few selected spectra captured by the system. The strange spot shapes of the captured spontaneous radiation and the high level of losses (>5%) in the cavity raised suspicions that the optical cavity is unstable which proved to be correct.

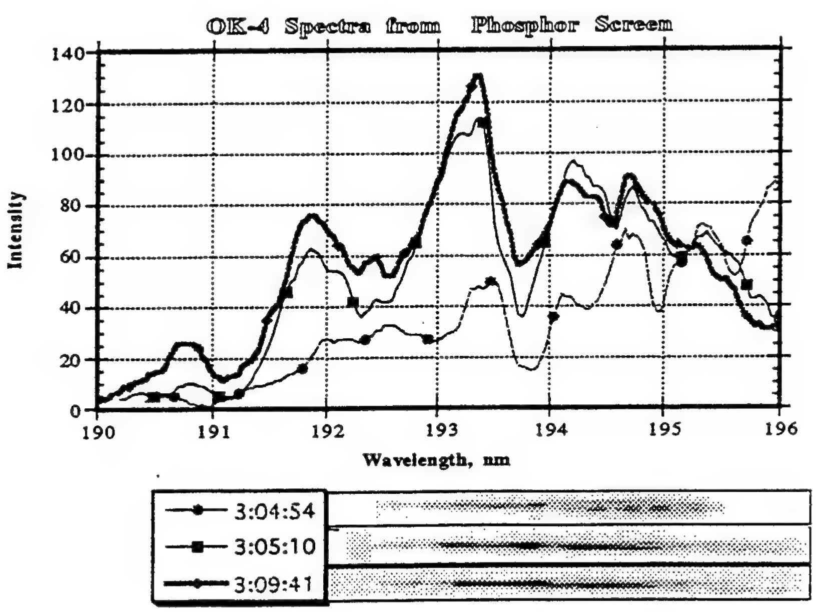

Fig.5. The spectra captured by a video camera from the phosphor screen installed at the exit of the monochromator on August 21, 1996 from 2:40 a.m. until 3:20 a.m. Energy of the electron beam is 500 MeV, K_w = 2.32, the plotted spectra were measured during a RF frequency scan. The period of the fine structure is about 1.3 nm and close to expectations. The video images of the spectra are shown below the graph . ● - time 3:04:54; current is 3.3 mA, maximum intensity around 193 nm is 50; ■ - time 3:05:10; current is 3.2 mA - maximum intensity around 193 nm is 115; ◆ - time 3:09:41; current is 3 mA - maximum intensity around 193 nm is 130.

Later studies (January, 1997) of the recorded images did show that even in these dire circumstances (unstable optical cavity and huge ripples in the buncher power supply) we observed the local saturation of the phosphor screen which may be indicative of lasing. We will repeat the 193 nm run with a stable system and measure a nice narrow lasing line around 193 nm before claiming lasing below 200 nm. We made a few runs in October 1996 with the streak camera measuring the bunch-lengthening of the electron beam. The last

run with 193 nm mirrors was to measure the length of the optical cavity. We arranged for one reflection from the upstream mirror and measured the time difference between direct and reflected pulses by varying the revolution frequency. This measurement confirmed that the optical cavity length was within ±0.2 mm from the design length. After recognizing the problems with the optical cavity, we replaced the 193 nm mirrors with 380 nm mirrors (using different mirror clamps).

5.2. Lasing in the UV - November/December 1996.

Demonstration of lasing in the near UV was a much easier task. After two hours of low current operation (to provide out-gassing of the down-steam mirror and to achieve a vacuum reading in the low 10^{-9} torr range) we attempted to lase at injection energy. It took less than two hours of e-beam and optical cavity alignment to obtain first lasing at 380 nm. Knowledge of the optical cavity length proved to be very useful. Within two hours lasing at 400 MeV and 500 MeV was demonstrated as well. A few days later we demonstrated lasing at 550 MeV using the maximum available (at that time 2.1 kA) current in the OK-4 wigglers. Monochromatic γ-rays (with 1% FWHM resolution) were produced by operating the OK-4/Duke storage ring FEL with two equally separated electron bunches. This mode provides for head-on collisions of the optical and electron beams at the center of the optical cavity, and the generation of γ-rays via Compton backscattering [13]. Small emittance of the electron beam ensures a high level of correlation between the observation angle and the energy of the generated γ-rays. These γ-rays were monochromatized by a lead collimator. Most of our shifts were dedicated to these studies and the results will be published elsewhere [1]. Some of the OK-4 FEL parameters were measured in parallel with the γ-ray experiments.

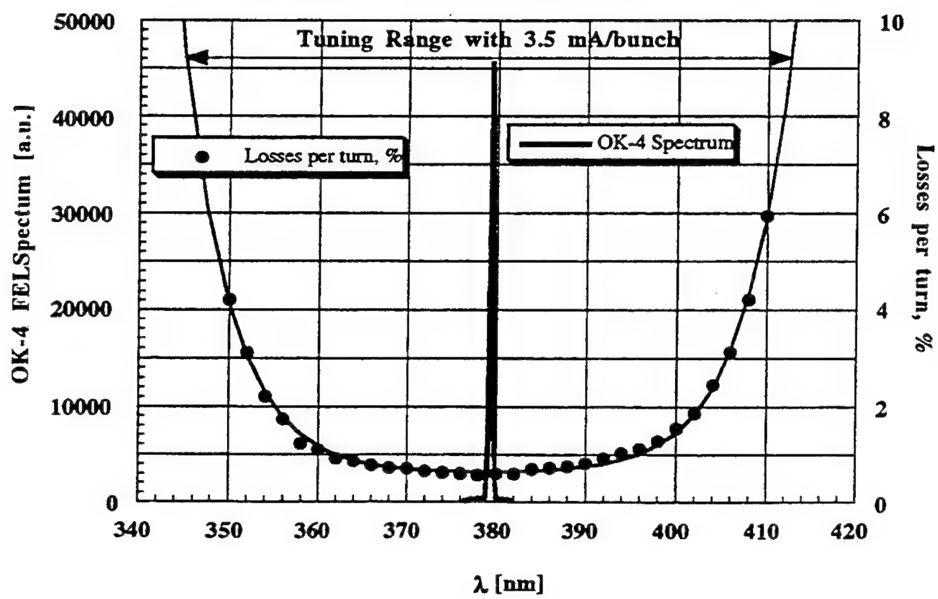

Fig. 6 The tuning range of the OK-4 FEL (with 3.5 mA/bunch at 500 MeV with 500 kV RF voltage) using 380 nm mirrors. The line in the center is a measured time average lasing line with RMS width of $\sigma_\lambda/\lambda=4.10^{-4}$ (which is presumably defined by small residual ripples in the power supplies). This line was tuned ±18% from 345 to 413 nm by changing the current in the OK-4 wigglers. The lasing range is determined by the growth of the cavity losses (mostly due to transparency of the mirrors) to the level of the OK-4 gain. The dots are measured round trip cavity losses and the smooth curve is a fit. Round-trip losses at the edges of the tuning range give the value of the FEL gain at a given current. From the above curve we have concluded that the OK-4/Duke storage ring FEL gain with 3.5 mA/bunch 500 MeV electron beam and 500 kV RF voltage exceeds 9% at 345 nm.

A typical tuning range and one measured lasing spectrum are shown in Fig.6. Tuning within the range was straightforward by variation of the wigglers' current. Optical cavity losses were determined by a measurement of the optical cavity ring down time (see Fig.7). We have tuned the OK-4 lasing wavelength to

the desirable value, kicked the electron beam to stop the lasing process, and measured the decay of the captured laser light. The damping time of the kicked beam was ~135 msec, i.e. much longer than the decay time of the laser light in the optical cavity. Lasing was reasonably easy because the OK-4 gain was at least 10-20 times higher than losses at 380 nm. The start-up current for lasing was 0.3 mA, and with 3 mA/bunch we were able to lase in both optical klystron (buncher on) and conventional FEL mode (buncher off). In all cases the optical klystron mode had higher gain and allowed us to lase with one or, if desired, two lasing lines (see Fig. 8).

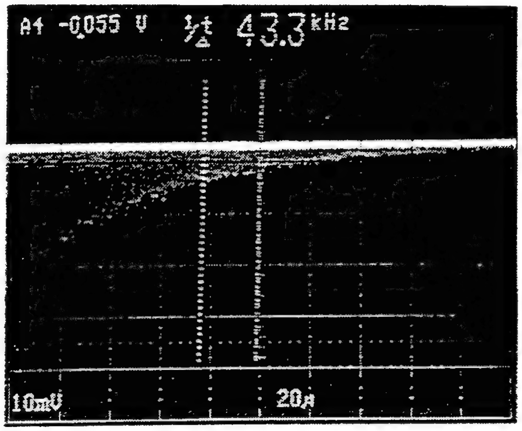

Fig. 7 The ring down of the OK-4 optical cavity at 377.5 nm. Horizontal scale is 20 msec per division.

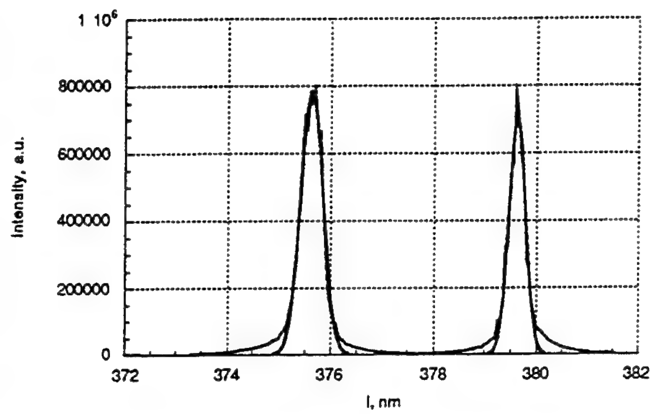

Fig. 8 Simultaneous lasing at two wavelengths in the OK-4/Duke FEL.

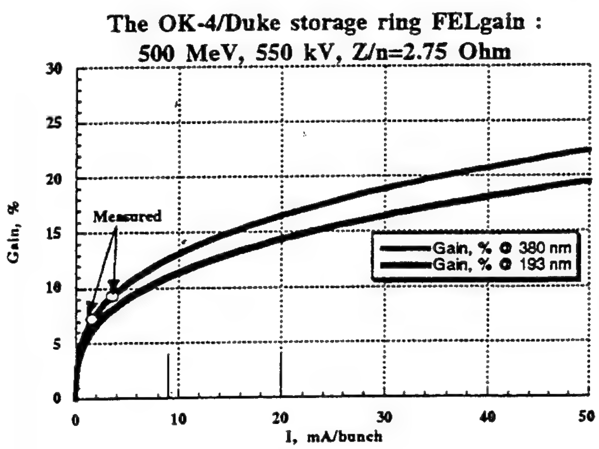

Fig. 9 The measured (dots, 345 nm) and predicted gain (solid lines) for 380 nm and 193 nm of the OK-4.

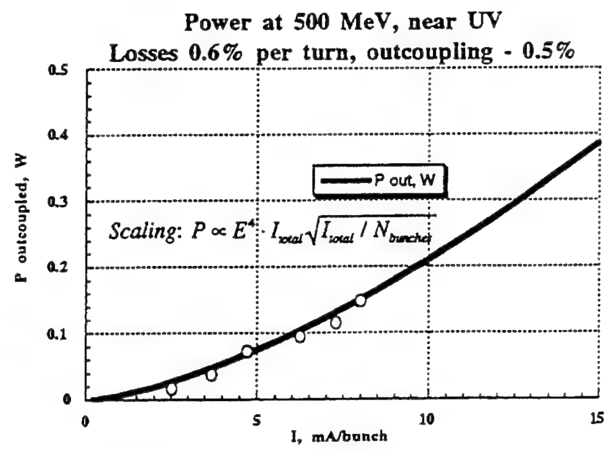

Fig. 10 Measured and predicted extracted lasing power from the OK-4 FEL. More than 80% of the power was extracted.

Figs. 9 and 10 show a comparison of the measured and predicted gain and extracted power from the OK-4 FEL in the near UV. We have used our self-consistent storage ring FEL code [14] and measured broadband (Z/n=2.75 Ohm) impedance model to predict the OK-4 performance. The FEL power was optimized by proper setting of the buncher current. We have used spontaneous radiation as a reference and a set of calibrated filters, a diaphragm, a monochromator and the transparency of the downstream mirror (measured by Lumonics Optics Group) to measure the extracted power. Expected accuracy is ±25%. At the present time we have an UV power meter and plan to repeat our measurements.

Indirect confirmation of the OK-4 FEL power was obtained from the observed γ-ray flux, which was within 20% of the predicted value [1]. The agreement of the measured and predicted values is very

reasonable and we can rely on our predictions of the OK-4 FEL gain at 193 nm. With expected cavity losses less than 3% [12], the OK-4 should lase at 193 nm with a beam current of a few mA/bunch. With 10 mA per bunch and existing set of mirrors, we expect to lase within the 188-197 nm range.

Starting from sub-mA currents, the electron bunch length is determined by the microwave instability. During lasing the FEL interaction induces an additional energy spread. We have observed the increase of the energy spread and bunch length by a factor of 2-3 during lasing. Typical RMS values of the FEL pulse were 5-10 times shorter than the electron bunch length. Operating at very low current and using very precise tuning of the revolution frequency, we have registered FEL micropulses as short as 2.5 psec RMS with the APS streak-camera. The duration of these pulses is consistent with Super-modes predicted in [15]. The results of these studies were consistent with our expectations and will be published separately [16]. Table III gives a short summary of the measured OK-4/Duke storage ring parameters.

The macrostructure of the FEL exhibited typical modes: pulsed, stochastic and DC depending on the RF frequency and tuning of the e-beam orbit in the OK-4. Oscillations of the laser power were caused by ripples in our power supplies. We plan to reduce these ripples to an acceptable level. We have used a crude "gain modulation" by applying 60 Hz AC voltage to one of our trim dipoles. In turn we observed repeatable macro-pulses with 120 Hz rep-rate. A proper gain modulator is in the process of design and construction. It will be used for generation of giant- and super-pulses in the OK-4 FEL. In this mode we expect harmonic generation in the VUV.

Table III. Measured Parameters of the OK-4 FEL

Tuning Range (3.5 mA/bunch)]	345-413 nm
Gain per pass (3.5mA/bunch, 345 nm)	>9%
Extracted Power (8 mA, single bunch, 380 nm)	0.15 W [a]
Induced e-bunch length, σ_s[ps]	
low current	~35
with 3.5 mA in single bunch	~200
Induced energy spread (3.5mA/bunch), σ_E/E	0.35%
FEL pulse length [ps]	
low current	~2.5
with 3.5 mA in single bunch	~20
Linewidth σ_λ/λ	$4 \cdot 10^{-4}$ [b]
Lasing life-time	2-4 hours

[a] Measured; 75 mW per mirror. Accuracy ~25%;

[b] Time averaged value presumably caused by ripples in power supply, instantaneous value should be $\sim 1 \cdot 10^{-4}$.

Absence of absorbers and permanent crotch chambers prevent us from operating at 1 GeV with full current and limits us to 10 mA at 750 MeV. With these beams we could not go far above a few watts of average laser power. The permanent crotch chambers and absorbers [17], which are nearly completed, are needed for full power (~100 W) operation of the OK-4/Duke storage ring FEL.

6. CONCLUSIONS AND PLANS

Commissioning the OK-4/Duke storage ring FEL demonstrated high performance of the cavity alignment, feedback, and control systems and reasonably high gain. Initial evaluation of the OK-4 FEL parameters is in good agreement with our predictions. We do not expect serious problems when we attempt to lase below 200 nm in the near future.

The gain modulator, the permanent crotch-chambers with absorbers, an UV optical room for the downstream mirror, and nitrogen purged beamlines are in progress. Later this summer we plan to begin use

of the OK-4 coherent and spontaneous radiation for user experiments. The user program includes eye surgery, studies of PMM, photo-absorption and spectroscopy.

7. ACKNOWLEDGMENTS

This work is supported by US Office of Naval Research Contract #N00014-94-0818, AFOSR Contract No.F49620-93-1-0590, DURIP-95 Grant F49620-95-1-0476 and Russian Academy of Sciences. The authors are grateful to P. Cable, G. Detweiler, H. Goehring, J. Gustavsson, M. Johnson, L. Kennard, C.Kornegay, H.Mercado, and J. Widgren (Duke University FEL Lab), V.V. Anashin, A. Bulygin, E.I.Gorniker, A.D.Oreshkov, V.M.Petrov, T.V.Shaftan, I.K.Sedlyarov, E. Szarmes. V.G.Vesherevitch (BINP, Novosibirsk) for their important contributions to the design, construction and commissioning of the OK-4 FEL. The authors would like to thank P.G.O'Shea, J.L.Lancaster (Duke University) and R.Jones (NCSU) for providing single-bunch injection capability. In addition we would like to acknowledge P.G.O'Shea for supervising operation of the linac injector and, J. Gustavsson and J. Widgren for keeping it operating all days and nights during the OK-4 FEL commissioning. The authors would like to thank R.S.Canon, C.R.Howell, N.R.Roberson, E.C.Schreiber, M.Spraker, W.Tornow and H.R.Weller (TUNL) for γ-ray measurements and characterization. In addition we would like to thank K.D.Straub for the development of the OK-4 FEL user program.

REFERENCES

[1] V.N.Litvinenko et al., "Gamma-ray Production in a Storage Ring Free Electron Laser", submitted for publication in Physics Review Letters.

[2] V.Litvinenko, J.M.J.Madey and N.A.Vinokurov, Proc. of 1993 Particle Accelerator Conference, Washington, DC, May 17-20,1993, v.2, p.1442.

[3] V.N.Litvinenko, "The optical klystron on VEPP-3 storage ring bypass - lasing in the visible and the ultraviolet", Thesis, Novosibirsk, 1989;
I.B.Drobyazko et al., Nucl. Instr. and Meth., A282 (1989) 424.

[4] V.N.Litvinenko et al., Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, V.I, p. 213.

[5] P.Wang, G.Kurkin, Y.Wu., Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p. 1841.

[6] P.G.O'Shea et al., "Single bunch injection...", to be published; P.G.O'Shea et al, Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p. 1090.

[7] Y.Wu et al., Nucl. Instr. and Meth., A375 (1996) p. 74.

[8] V.N.Litvinenko et al., Nucl. Instr. and Meth., A375 (1996) p. 46.

[9] A.Lumpkin, B.Yang, Argonne National Laboratory, Private communication.

[10] Y.Wu, B.Burnham, V.N.Litvinenko, "The Duke Storage Ring Control System" Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p.2214.

[11] I.V.Pinayev et al., "Diagnostics for the OK-4/Duke storage ring XUV FEL", Presented at 18th International FEL conference, Rome, Italy, August 26-31, 1996, to be published.

[12] S.H.Park et al., "Study of stability and thermal distortion of the optical resonator for the OK-4 /Duke XUV FEL", Presented at 18th International FEL conference, Rome, Italy, August 26-31, 1996, to be published.

[13] V.N.Litvinenko and J.M.J.Madey, Nucl. Instr. and Meth., A359 (1996) 580;
V.N.Litvinenko and J.M.J.Madey, SPIE v.2521 (1995) 55.

[14] V.N.Litvinenko, Nucl. Instr. and Meth., A359 (1995) 50;
V.N.Litvinenko et al., Nucl. Instr. and Meth., A358 (1995) p.334, p.369.

[15] G.Datoli et al., Phys. Rev. A (April, 1988).

[16] V.N.Litvinenko, A.Lumpkin, et al., "Study of the microtemporal structure of the OK-4/Duke UV FEL", to be published.

[17] V.N.Litvinenko et al., SPIE v.2522 (1995) p. 473.

PAC'97

UNIQUE FEATURES OF THE OK-4/DUKE STORAGE RING XUV FEL AND MONOCHROMATIC γ-RAY SOURCE.

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Abstract

The OK-4 is the first storage ring FEL operating in the United States. It was commissioned in November, 1996 and demonstrated lasing in the near UV and visible ranges (345-413 nm) with extracted power of 0.15 W [1]. In addition to lasing, the OK-4/Duke FEL generated a nearly monochromatic (1% FWHM) γ-ray beam [2]. In this paper we describe the initial performance of the OK-4 /Duke storage ring FEL and γ-ray source.

1. INTRODUCTION

The OK-4 /Duke storage ring FEL project is a collaboration of the Duke University Free Electron Laser Laboratory and the Budker Institute of Nuclear Physics begun in 1992 [3]. The OK-4 FEL was built and operated in the 240-690 nm range using the VEPP-3 storage ring at Novosibirsk [4]. After commissioning the 1.1 GeV Duke storage ring in November, 1994 [5], the OK-4 FEL made a trip around the globe to Duke in May, 1995. The OK-4/Duke FEL was ready for the first demonstration experiment in November, 1996. The first run on November 13, 1996 with the OK-4/Duke FEL was successful. The OK-4/Duke storage ring FEL demonstrated operation in the near UV/visible range and generated nearly monochromatic 3-15 MeV γ-rays via intracavity Compton backscattering.

2. THE OK-4/DUKE XUV STORAGE FEL

The Duke 1.1 GeV storage ring [5,9] has a 34 meter long straight section dedicated for FEL operation. The present lattice has transverse β-functions of 4 meters in both directions at the center of the OK-4 to optimize the gain. The storage ring RF system [7] operates at 178.5 MHz (64th harmonic of the revolution frequency). Typical OK-4 FEL operation mode applies an RF voltage of 500 kV. The existing 270 MeV injection system limits the maximum stored current to 8 mA/bunch. We plan to improve the efficiency of injection and increase single bunch current to 20-40 mA. Some parameters of the Duke storage ring are summarized in Table I. The main parameters and expected performance of the OK-4 FEL are described in previous publications [4,10]. Table II gives an up-to-date summary of the parameters. The magnetic system of the OK-4 FEL was slightly modified to accommodate a new vacuum chamber and to provide a field-free collision point for the Compton γ-ray source. Two Trans-Rex power supplies (5 kA, 500 V, donated by Fermi Lab) have been repaired, equipped with large external LC filters and are presently used to drive the OK-4 wigglers and buncher. Overall performance of the OK-4 power supplies is close to specifications (50 ppm DC and ripples) and will be improved in the near future using a second stage of regulation and feedback. The controls of the OK-4 FEL are part of the Duke storage ring computer control system [11]. This system provides flexible operation of the OK-4 and the possibility to ramp the energy of the storage ring without changing the OK-4 wavelength.

Table I. Duke Storage Ring Electron Beam Parameters

Operational Energy [GeV]	0.25-1.1
Circumference [m]	107.46
Impedance of ring, Z/n, [Ω]	2.75±0.25
Stored current [mA][a] multibunch	155
single bunch	20[b] /8[c]
Bunch length, σ_s[ps][d] natural	15
with 5 mA in single bunch	60
Relative Energy spread, σE/E[d] natural	$2.9.10^{-4}$
at 5 mA in single bunch	$1.1.10^{-3}$
Peak Current [A][d] with 5 mA/bunch	12
with 20 mA/bunch[e]	31
Horizontal Emittance [nm*rad]	
5 mA/ bunch @ 700 MeV	< 10[f]
3 mA/ bunch @ 500 MeV	< 8[f]

[a] *Maximum current at 1 GeV is limited to 2-3 mA before crotch-chambers with absorbers are installed;*
[b] *Per bunch using standard mode of multibunch injection;*
[c] *In single injection mode with 1 nsec photocathode gun [8];*
[d] *At 500 MeV, V_{RF}=500 kV;*
[e] *Expected from broad band impedance model with Z/n = 2.75Ω;*
[f] *Extracted from the OK-4 spontaneous radiation spectra.*

Table II. OK-4 FEL Parameters Optical Cavity

Optical cavity length [m]	53.73
Radius of the mirrors [m]	27.27[a]
Rayleigh Range in OK-4 center [m]	3.3
Angular control accuracy [rad]	better than 10^{-7}
OK-4 wiggler [4,10]	
Period [cm]	10
Number of periods	2 x 33.5
Gap [cm]	2.25[b]
Kw/I [1/kA]	1.804
Kw	0-5.4

[a] *Measured;* [b] *Increased to accommodate new vacuum chamber.*

We have installed temporary crotch chambers (*without absorbers and smooth transitions*) providing passage of the OK-4 optical beam to facilitate its commissioning. This makes the impedance of the vacuum chambers rather large.

According to the bunch length and the OK-4 FEL gain measurements, the impedance of the vacuum chamber is ~2.75 Ohm.

3. COMMISSIONING OF OK-4 FEL AND γ-RAY SOURCE

Three main storage ring operational modes were established (injection energy of 0.265 GeV, at 0.5 GeV and 0.7 GeV the OK-4) along with a number of supplementary modes (between 0.35 and 0.75 GeV) for proper FEL operation. We have created computer tools to vary the OK-4 wiggler current while keeping the betatron tunes stable. It took less than two hours to obtain first lasing. Knowledge of the optical cavity length proved to be very useful [6]. Lasing was demonstrated at a variety of electron energies from 0.265 to 0.55 GeV. A standard operation energy was 500 MeV.

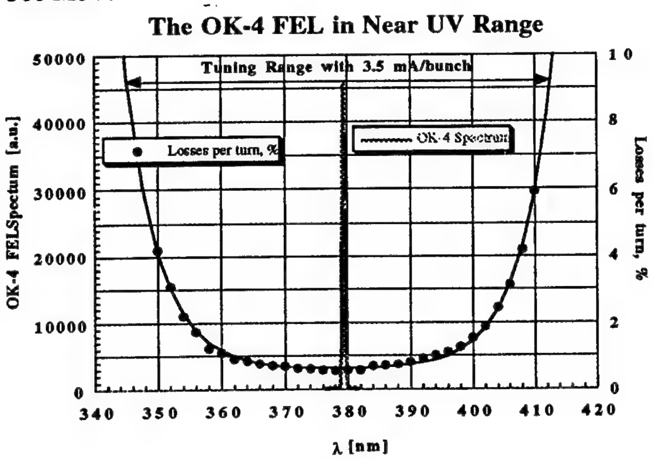

Fig. 1 The tuning range of the OK-4 FEL (with 3.5 mA/bunch at 500 MeV with 500 kV RF voltage) using 380 nm mirrors. The line in the center is a measured time lasing line. This line was tuned ±18% from 345 to 413 nm by changing the current in the OK-4 wigglers. The dots are measured round trip cavity losses and the smooth curve is a fit. Round-trip losses at the edges of the tuning range give the value of the FEL gain at a given current: gain >9% at 345 nm with 3.5 mA/bunch, 500 MeV electron beam and 500 kV RF voltage .

A typical tuning range (obtained by variation of the wigglers' current) and one measured lasing spectrum are shown in Fig.1. Lasing was reasonably easy because the OK-4 gain was at least 10 times higher than its losses at 380 nm. The start-up current for lasing was 0.3 mA, and with 3 mA/bunch we were able to lase in both optical klystron and conventional FEL mode (buncher off). In all cases the optical klystron mode had higher gain and power. Figs. 2 and 3 show a comparison of the measured and predicted gain and extracted power from the OK-4 FEL in the near UV. We have used our self-consistent storage ring FEL code [13] and broadband impedance model to predict the OK-4 performance. The agreement of the measured and predicted values is very reasonable and we can rely on our predictions of the OK-4 FEL gain at 193 nm.

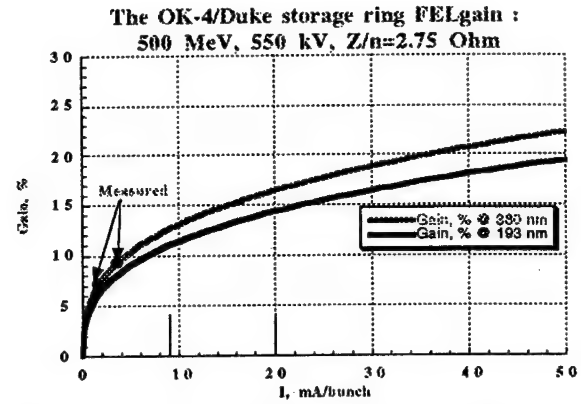

Fig. 2 The measured (dots, 345 nm) and predicted gain (solid lines) for 380 nm and 193 nm of the OK-4.

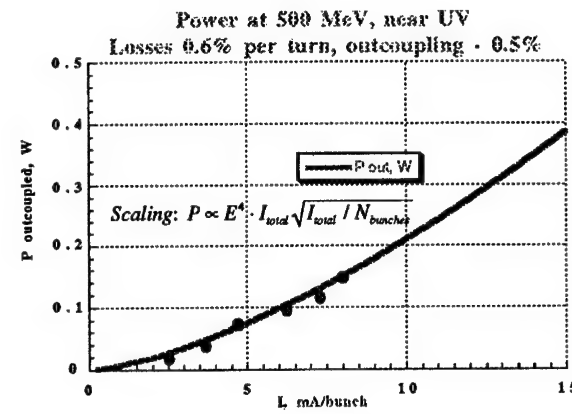

Fig. 3 Measured and predicted extracted lasing power from the OK-4 FEL. More than 80% of the power was extracted.

Table III. Measured Parameters of the OK-4 FEL

Tuning Range (3.5 mA/bunch)]	345-413 nm
Gain per pass (3.5mA/bunch, 345 nm)	>9%
Extracted Power (8 mA, 380 nm)	0.15 W
Induced e-bunch length, σs[ps]	
low current	~35
with 3.5 mA in single bunch	~200
Induced energy spread (3.5mA/bunch), σE/E	0.45%
FEL pulse length [ps]	
low current	~2.5
with 3.5 mA in single bunch	~20
Linewidth σ_λ/λ	$4 \cdot 10^{-4}$ [b]
Lasing life-time	2-4 hours

[a] *Measured; 75 mW per mirror. Accuracy ~ 25%;*
[b] *Time averaged value presumably caused by ripples in power supply, instantaneous value should be ~$1 \cdot 10^{-4}$.*

With expected cavity losses less than 3% [1], the OK-4 should lase at 193 nm with a beam current of a few mA/bunch. With 10 mA per bunch and existing set of mirrors, we expect to lase within the 188-197 nm range.

We have observed an increase of the energy spread and bunch length by a factor of 2-3 during lasing. Typical RMS values of the FEL pulse were 5-10 times shorter than the electron bunch length. Operating at very low current and using very precise tuning of the revolution frequency, we have registered FEL micropulses as short as 2.5 psec RMS with the APS streak-camera. The duration of these pulses is consistent with Super-modes predicted in [14]. Table III gives a summary of the measured OK-4/Duke storage ring parameters.

Monochromatic γ-rays (with 1% FWHM resolution) were produced by operating the OK-4/Duke storage ring FEL with two equally separated electron bunches. This mode provides for head-on collisions of the optical and electron beams at the center of the optical cavity, and the generation of γ-rays via Compton backscattering [12]. Small emittance of the electron beam ensures a high level of correlation between the observation angle θ and the energy of the generated γ-rays:

$$E_\gamma = \frac{4\gamma^2 E_{ph}}{1+(\gamma\theta)^2 + 4\gamma E_{ph}/mc^2};\ E_{ph} = \hbar\omega; \gamma = \frac{E_e}{mc^2}$$

A simple collimator can be used to select the most energetic γ-rays near θ=0. Using a lead collimator with 3 mm diameter (located 30 m downstream from the collision point) and a Ge detector we measured the 1% FWHM energy resolution of the γ-rays. We demonstrated the tunability of γ-ray energy within the 3-15 MeV range tuning both the laser wavelength (±18%) and the energy of the electron beam (265-550 MeV). Most of our shifts were dedicated to these studies and the results will be published elsewhere [2].

After one month of operation, which was mostly dedicated to γ-ray generation and spectrum measurements, the injector for the storage ring was shut down in December, 1997 to condition one of the klystrons. We expect to resume operation of the OK-4 FEL when conditioning is finished.

4. CONCLUSIONS AND PLANS

Commissioning the OK-4/Duke storage ring FEL demonstrated high performance and reasonably high gain. Initial evaluation of the OK-4 FEL parameters is in good agreement with our predictions. We do not expect serious problems when we attempt to lase below 200 nm in the near future. The gain modulator, the permanent crotch-chambers with absorbers, and nitrogen purged beamlines are in progress. The gain modulator will provide for high intracavity power and generation of coherent VUV harmonics. Later this year we plan to begin use of the OK-4 coherent and spontaneous radiation as well as monochromatic γ-rays for user experiments. The user program includes nuclear γ-ray spectroscopy, UV cornea surgery, studies of PMM, photo-absorption and spectroscopy.

Absence of absorbers and permanent crotch chambers prevent us from operating at 1 GeV with full current and limits us to 10 mA at 750 MeV. With these beams we could not go far above a few watts of average laser power. The permanent crotch chambers and absorbers [15] are needed for full power (~100 W) operation of the OK-4/Duke storage ring FEL and full flux operation of the γ-ray source (10^9-10^{11} γs/sec). We plan to install them in 1998. Long term plans for the OK-4 include extension to the VUV range.

5. ACKNOWLEDGMENTS

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REFERENCES

[1] V.N.Litvinenko et al., SPIE v.2988 (1997) p.188.
[2] V.N.Litvinenko et al., "Gamma-ray Production in a Storage Ring Free Electron Laser", to be published in Physics Review Letters.
[3] V.Litvinenko et al.,, Proc. of PAC'93 ,1993, p.1442.
[4] I.B.Drobyazko et al., NIM A282 (1989) 424.
[5] V.N.Litvinenko et al., Proc. of PAC, 1995, p. 213.
[6] A.Lumpkin et al., "Initial applications of a Dual-Sweep streak camera for the Duke SR OK-4 source", These Proceedings.
[7] P.Wang et al., Proc. of PAC'95, 1995, p. 1841.
[8] P.G.O'Shea et al., "Single bunch injection for SR FEL.", These Proceedings.
[9] Y.Wu et al., NIM A375 (1996) p. 74.
[10] V.N.Litvinenko et al., NIM A375 (1996) p. 46.
[11] Y.Wu et al., Proc. of PAC'95, 1995, p.2214.
[12] V.N.Litvinenko, J.M.J.Madey, NIM A359 (1996) 580; V.N.Litvinenko et al., SPIE v.2521 (1995) 55.
[13] V.N.Litvinenko, NIM A359 (1995) 50; V.N.Litvinenko et al., NIM A358 (1995) pp.334, 369.
[14] G.Datoli et al., Phys. Rev. A (April, 1988).
[15] V.N.Litvinenko et al., SPIE v.2522 (1995) p. 473.

High power Inverse Compton γ-Ray source at Duke storage ring.

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ABSTRACT

A 1.1 GeV electron storage ring dedicated for UV-VUV FEL operation was commissioned last year at the Duke University Free Electron Laser Laboratory (DFELL) [1]. The UV-VUV OK-4 FEL project, based on the collaboration of the Duke FEL Laboratory and Budker Institute for Nuclear Physics (BINP, Novosibirsk, Russia) is under way. The OK-4 FEL has arrived from Novosibirsk at the Duke FEL laboratory and is in the process of installation.

High average intracavity power and natural synchronization of electron and optical pulses in the OK-4 FEL allow to produce intense beam inverse Compton 5-150 MeV γ-rays on return pass of optical pulse. The projected intensity of this γ-ray source allows high energy resolution with the use of simple geometrical collimating of γ-rays. The wide tunability of the OK-4 FEL allows also to control γ-rays energy.

In this paper we discuss the processes involved, the influence of beam parameters and geometry on γ-ray energy spread and present projected performance of the Duke/OK-4 inverse Compton γ-ray source for two simple cases. The study reported in this paper have been done in 1993. Results were presented at 1994 Free Electron Laser Conference (22-26 August 1994, Stanford, CA) but were published only as internal DFELL report [2]. A group of scientists from the Triangle University Nuclear Laboratory (TUNL) has carried independent simulations in 1994 which confirm our predictions.

A workshop on DFELL-TUNL γ-ray facility was held in Durham on December 16-17, 1994 to discuss unique features of this facility and its utilization for nuclear physics and pion spectroscopy [4].

1. INTRODUCTION

1.1 Inverse Compton scattering.

Inverse Compton scattering (ICS) is well known and well exploited effect to produce γ-rays using ultrarelativistic electrons [5]. Most of storage ring ICS sources use visible or UV lasers to collide them "head-to-head" with ultrarelativistic electrons. This lasers should work in mode-locking regime to provide short pulses synchronized with electron bunches in storage ring. Inverse Compton scattering of optical photons on ultrarelativistic electrons boost their energy to γ-rays.

We are intended to use UV intracavity photons of OK-4 FEL for same purpose. In addition to very high intracavity power, FEL photons are naturally aligned and synchronized with electron beam.

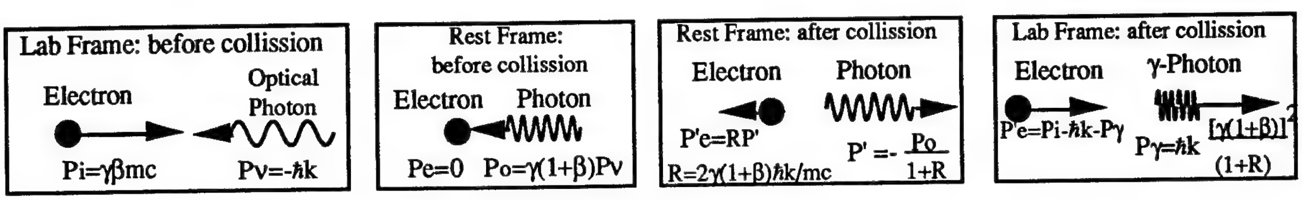

Fig. 1 Inverse Compton scattering: the kinematics.

The processes for inverse Compton scattering are illustrated by Fig.1. The process involves an ultrarelativistic electron and an optical photon propagating in opposite directions. In the laboratory frame the electron and photon parameters are defined by:

$$E_e = \gamma mc^2; \quad \vec{p}_e = \gamma mc\vec{v}; \quad \beta = \frac{v}{c}; \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}; \quad E_{vin} = \hbar\cdot\omega; \ \vec{p}_{vin} = \hbar\cdot\vec{k}; \ k = \omega / c; \qquad (1)$$

where $E_e, \bar{p}_e, v, \gamma$ are the energy, momentum, velocity and relativistic factor (in our case $\gamma >> 1$; $1-\beta \approx 1/2\gamma^2 << 1$) of the electron; and E_{vin}, $\bar{p}_{vin}, \omega, \bar{k}$ are energy (eV range), momentum, frequency and the wavevector of the photon, m is the electron mass, c is the speed of the light and $\hbar$ is Plank constant.

In the rest frame of electron, the photon energy is boosted up by factor $\gamma(1+\beta)$ ($\cong 2\gamma$) to the keV X-ray range. The most interesting photons are those which are scattered in the direction opposite their initial direction, i.e. inverse Compton photons. Their energy is reduce by factor (1+R), where R is the recoil:

$$R = \frac{2\gamma(1+\beta)E_{vin}}{mc^2} \equiv \frac{2\gamma^2(1+\beta)E_{vin}}{E_e} \cong \frac{4\gamma^2 E_{vin}}{E_e}. \tag{2}$$

Transition back to the laboratory frame is identical to previous (photon propagation is opposite to the frame velocity). Thus, the photon gain additional factor $\gamma(1+\beta)$ in its energy and becomes a γ-ray (MeV range):

$$E_\gamma = \hbar\omega \frac{[\gamma(1+\beta)]^2}{1+R} = \hbar\omega \frac{[\gamma(1+\beta)]^2}{1+\frac{2\gamma(1+\beta)\hbar\omega}{mc^2}} \cong \frac{4\gamma^2\hbar\omega}{1+\frac{4\gamma\hbar\omega}{mc^2}}. \tag{3}$$

The recoil parameter can be expressed trough E_γ and initial electron energy:

$$R = \frac{\frac{E_\gamma}{E_e}\frac{2}{(1+\beta)}}{1-\frac{E_\gamma}{E_e}\frac{2}{(1+\beta)}} \cong \frac{\frac{E_\gamma}{E_e}}{1-\frac{E_\gamma}{E_e}}; \tag{4}$$

which means that recoil is essential when energy of γ-ray is comparable with initial electron energy $E_\gamma \sim E_e$. It is also evident that energy of γ-ray can not exceed those of the electron: equation (3) can be reduced to the form which clearly state it:

$$E_\gamma = \frac{\gamma mc^2}{1+\frac{\gamma mc^2}{2\gamma^2(1+\beta)\hbar\omega}} \cdot \frac{1+\beta}{2} < \gamma mc^2 = E_e. \tag{5}$$

When recoil is small (R<<1) and simple approximate ratio $E_\gamma \cong 4\gamma^2\hbar\omega$ can be used: energy of ICS γ-rays is then $4\gamma^2$ times energy of initial photon. Typical energies of electron storage ring used for ICS are from 1 GeV to 10 GeV. In this case γ ranges from 2,000 to 20,000, $4\gamma^2$ ranges from $16 \cdot 10^6$ - $16 \cdot 10^8$. The use of visible and UV photons with E_{ph}=2-10 eV with 1 GeV electrons will provide for E_γ=32-139 MeV (maximum recoil is R=0.153). The same photons with 10 GeV electrons would generate E_γ=2.77 - 6.24 GeV γ-rays (recoil is very important here: γ=20,000, E_{ph}=10 eV give R=1.57).

1.2 The Duke storage ring

The Duke FEL electron storage ring is designed to drive UV and soft X-ray FELs. One of the two 34-meter straight sections is dedicated for FEL installation. The other straight section is used for injection, installation of the RF cavity, diagnostic systems, and NIST undulator (soft X-ray source). The main parameters of the Duke storage ring are summarized in Table I. Layout and detailed information on the Duke storage ring can be found in Ref. [1] and ref. [6], which is published in these Proceedings.

The RF system of the Duke storage ring operates on 64-th harmonic of revolution frequency and can support maximum of 64 electron bunches. We are considering the use of two bunches (or two short trains of bunches) for γ-ray production .

Table I. Parameters of Duke Storage Ring

Storage ring	Design	Measured/Achieved [1]	Comment
Ring circumference [m]	107.46	107.46±0.003	Central orbit
Operating energy [GeV]	0.25 - 1.0	0.2-1.1	With ramping
Injection energy [GeV]	0.25 - 1.1	0.2-0.28	0.5 (1996), 1.1 GeV (1997)
RF frequency - 64 th harmonic [MHz]	178.547	178.547±0.046	Tuning range
Energy acceptance, ΔE/E, of ring	>±5.0%	±6 %	
Maximum β-functions [m], x and y	13.6, 21.3	12.92; 21.81	Without tuning*
Maximum η-function [m]	0.245		
Electron beam	Design	Measured/Achieved	Comment
Beam current, A	0.1 (1.0***)	0.115	In 5 bunches
Horizontal emittance, m*rad	$18\cdot10^{-9}$	$17\text{-}19\cdot10^{-9}$	At 1 GeV
Vertical emittance, m*rad	$1\cdot10^{-9}$	$<1\cdot10^{-9}$	
Bunch length, ps	33	< 70**	
Relative energy spread (low current)	0.0005		
at peak current of 130 A	0.0016		
Beam size in OK-4 [mm], σx and σy	0.27; 0.085		

* *these values are for theoretical settings; they are corrected to desirable values;*
** *limited by the instrument resolution; requires verification;* *** *final specification of the ring.*

1.3. Projected performance of DUKE/OK-4 XUV FEL

The OK-4 was the first operational UV FEL demonstrating lasing down to 240 nm. It still holds the short wavelength record for FELs. The OK-4 magnetic system and its projected performance are described in Refs. [7] and in Ref. [6] (these Proceedings).

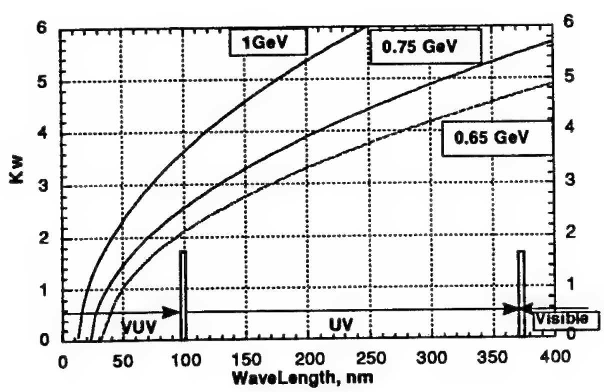

Figure 2. OK-4 tuning range at 0.65, 0.75 and 1 GeV.

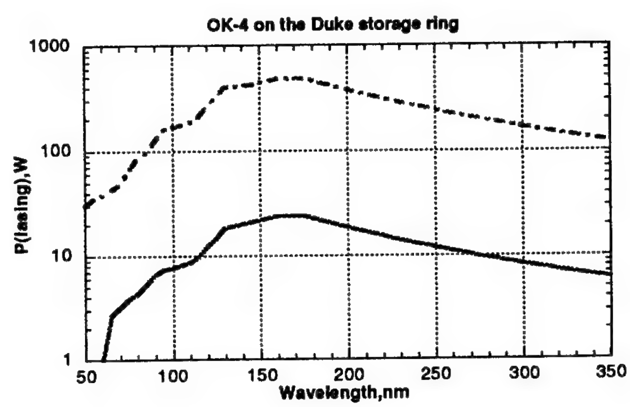

Figure 3. OK-4 FEL lasing power: solid line for 100 mA and dashed curve for 1 A average current.

The tuning range of the fundamental harmonic wavelength of the OK-4 FEL is shown in Figure 2. The expected OK-4 average CW lasing power for 100mA and 1A average current are plotted in Figure 3. The other parameters of the OK-4/DUKE UV-VUV FEL are presented in Table III.

Table II. Parameters OK-4/DUKE UV-VUV FEL

Tuning range, [nm]:	fundamental:	50-400	harmonics	4-100
Linewidth, [$\delta\lambda/\lambda$]	natural	(1-3) 10^{-4}	with linewidth narrowing	(5-30) 10^{-7}
Micropulse duration [psec]	natural	3-30	in super-pulse mode	0.1-2
Micropulse separation [nsec]	one bunch	358.45	64 bunches 5.60	
Spatial distribution	TEMoo			

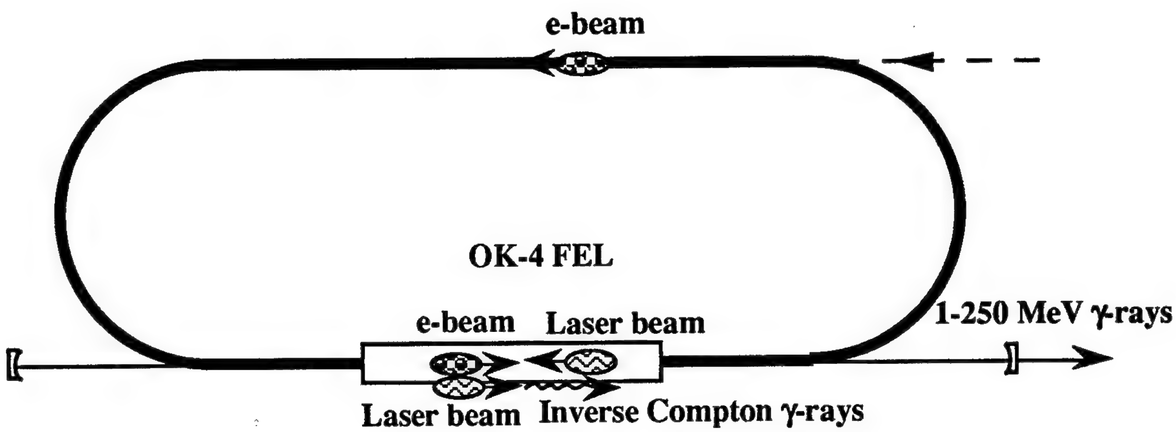

Fig. 4. Schematic of γ-ray source at Duke FEL Laboratory.

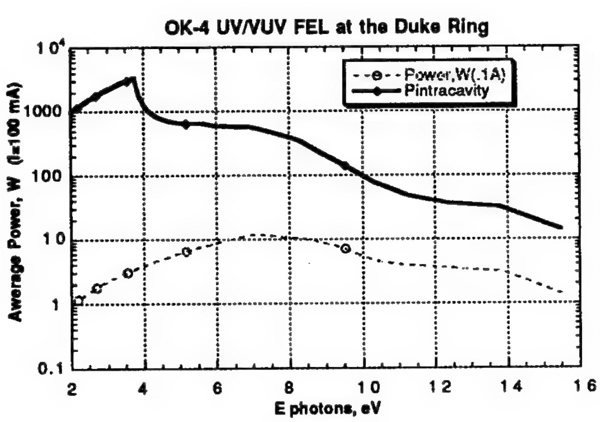

Fig. 5 Plot of the average lasing power and average intracavity power (solid line) in OK-4 FEL operating at the Duke storage ring.

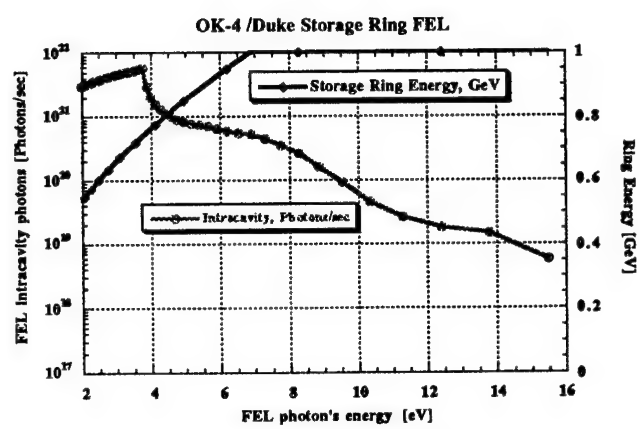

Fig. 6 Plot of the ring energy and number photons per second passing through the OK-4 FEL optical cavity.

1.4. γ-Rays production.

Fig. 4 shows schematic of the γ-ray source at Duke. The OK-4 FEL is located in the center of the straight section. Its optical cavity has the length exactly equal to the half of the ring circumference for FEL to operate in synchronism with electron bunches. Lets consider one electron bunch in the ring. While passing through the FEL, the electron bunch amplify optical radiation and support coherent optical pulse which is 5-6 times shorter then electron bunch. When optical pulse returns back reflected by front mirror, the electron bunch is located in opposite straight section.

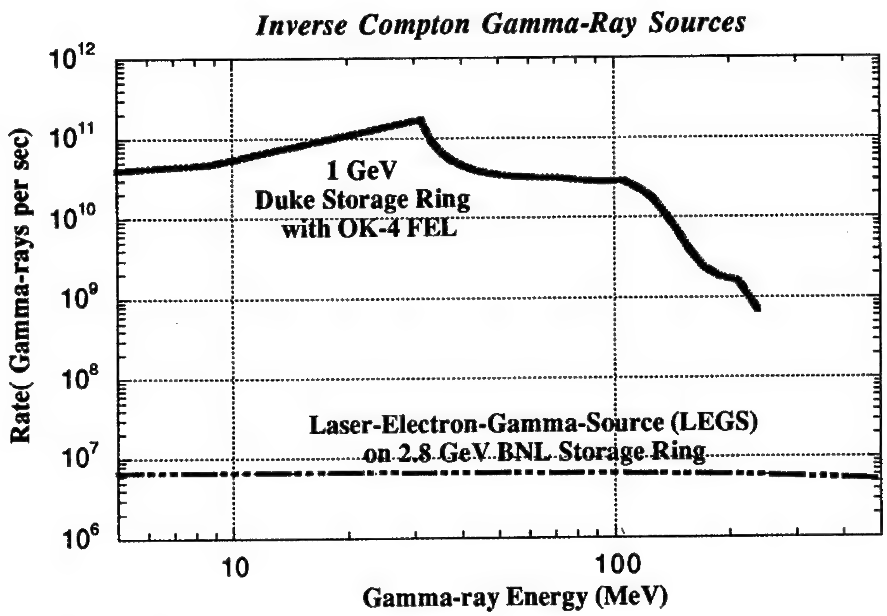

Fig. 7 Predicted rate for the OK-4/Duke ring γ-ray source compared with the LEGS facility [5].

By storing two electron bunches separated by half of the ring circumference we would create a collision point in the center of the FEL. Now, on its way back, the optical pulse collides 'head-to-head" with second electron bunch and generates ICB γ-rays. This process then repeats each half of the revolution period.

There are many important advantages in the use of this concept:

a) In order to operate FEL, both electron and optical beam must be perfectly aligned. Thus, "head-to-head" collisions is automatically provided by FEL operation.
b) This scheme uses kW levels of average and GW levels of peak intra-cavity optical power to generate intense γ–ray beam.
c) FEL laser beam is a precise and natural pointer in the direction of γ-ray cone center.
d) High flux and natural pointer allow to use a simple collimators to select 100% polarized γs with maximum energy. Energy resolution is defined by geometry. NO TAGGING REQUIRED!
e) Low emittance of the Duke ring provides for monochromatic γ–ray beam on target.
f) NO TAGGING means that γ–rate is not limited by revolution frequency. Tagging measures energy of γ-rays by measuring energy of lost electrons. Thus, even analyzing electronics could measure energy of two or more lost electrons per turn, nothing can identify what are energies of each γ-ray.
g) Optical pulses are naturally synchronized with electron bunches and cancel jitter.
h) FEL and storage ring are widely tunable which provides 240 fold tunability of γ-ray energy (15 in OK-4 x 2^4 in energy). Thus, 100% polarized 4 MeV to 250 MeV (up to 1 GeV with spontaneous radiation) γ-rays can be produced. Continuous tuning of FEL will allow to scan energy of γ-rays.
i) Time structure (CW, pulse, reprate, etc.) can be adjusted to the user needs using flexibility of the FEL.
j) 100 %, Arbitrary tunable polarization (linear or L/R circular) using special wiggler (OK-4 will provide only linear polarization, modifications are required for elliptical polarization).

The Duke storage ring demonstrated operation in energy from 0.2 GeV to 1.1 GeV (and it is capable of 1.2-1.3 GeV if it is necessary). The OK-4 FEL will operate in the visible, the UV and the VUV range with photons energy of 2 to 15 eV. Thus, this facility could provide γ-rays from 1.5 MeV (at 0.2 GeV with 2 eV photons) to 222 MeV (at 1.1 GeV with 15 eV photons where R=0.253).

It is important to mention, that production of γ-rays with energy less then 5% of electrons energy would not lead to the loss of electrons. This electron would survive the energy shock, because of very large (>±5%) energy acceptance of the Duke storage ring. It means that production of low energy γ-rays ($E_\gamma \leq 35$ MeV γ-rays at 700 MeV ring energy or $E_\gamma \leq 50$ γ-rays at 1 GeV) do not require refill of electrons. Their energy loss will be compensated by the ring RF system.

Predicted average intracavity power, which is important for ICB γ-rays, for the OK-4/Duke FEL with 100 mA e-beam current is shown on Fig. 5. Average intracavity power is from 20W at 15 eV to 4 kW at 3.5 eV. This levels of power make the Duke γ-ray source very. Intracavity power can be easily translated into number of optical photons per second passing the OK-4 optical cavity. Fig.6 shows this graph and also the maximum energy of the ring should operate required photon energy. Predicted performance of the Duke FELL gamma-source is presented on Fig. 7.

2. PHOTON SCATTERING ON ELECTRON - REVIEW OF THEORY.

In this paragraph we consider a brief theoretical description using exact relativistic invariant formulae for the kinematics of the process [8], and quantum electrodynamics formulae for cross-section and γ-rays distribution [9]. These relativistic invariant formulae can be used in any frame (lab, rest, etc.) without modifications.

We will use standard QED units ($\hbar$=c=1) in this chapter for compactness of expressions, while presenting all final answers in practical or SGS units. For example, the parameters of the electron are:

QED units $$\mathrm{E} = \gamma m; \quad \vec{\beta} = \vec{v}; \quad \beta = v; \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}; \ \mathrm{p} = \beta \mathrm{E}; \quad \vec{\mathrm{p}} = \vec{\beta}\mathrm{E}; \tag{6}$$

SGS units $$E = \gamma mc^2; \quad \vec{\beta} = \vec{v}/c; \quad \beta = v/c; \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}; \ pc = \beta E; \quad \vec{p}c = \vec{\beta}E; \tag{6'}$$

and photon parameters are:

QED units $$E = \omega; \quad \vec{p} = \vec{k}; \quad \vec{k} = \vec{n}\omega; \ k = \omega; \ |\vec{n}| = 1; \tag{7}$$

SGS units $$E = \hbar\omega; \quad \vec{p} = \hbar\vec{k}; \quad \vec{k} = \vec{n}\,\omega/c; \ |\vec{n}| = 1. \tag{7'}$$

2.1 The kinematics and the energy of scattered photons.

Relativistic invariant scattering kinematics can be derived from the conservation of 4-momentum:

$$p + k = p' + k' \tag{8}$$

which is equivalent to standard conservation laws $\mathrm{E} + \hbar\omega = \mathrm{E}' + \hbar\omega'$; $\vec{\mathrm{p}} + \hbar\vec{k} = \vec{\mathrm{p}}' + \hbar\vec{k}'$; where p' and k' are 4-momenta of electron and photon after interaction and p and k - before interaction:

$$p = (E, \vec{\mathrm{p}}), \qquad k = (\omega, \vec{\mathrm{k}}). \tag{9}$$

Simple calculations give the energy of scattered photon (in regular unit):

$$\hbar\omega' = \hbar\omega \cdot \frac{\mathrm{E} - \mathrm{p}c \cdot \cos\theta_i}{\mathrm{E} + \hbar\omega - \mathrm{p}c \cdot \cos\theta_f - \hbar\omega \cdot \cos\theta_{ph}} = \hbar\omega \cdot \frac{1 - \beta \cdot \cos\theta_i}{1 - \beta \cdot \cos\theta_f + \hbar\omega / \mathrm{E} \cdot \left(1 - \cos\theta_{ph}\right)}; \tag{10}$$

where θ_i is an angle between momentum of electron $\bar{\mathbf{p}}$ and direction of initial photon $\bar{k}$; θ_f is an angle between momentum of electron $\bar{\mathbf{p}}$ and direction of scattered photon $\bar{k}'$; θ_{ph} is an angle between directions of photons $\bar{k} \wedge \bar{k}'$. In spherical coordinates (r, θ, φ) the angles $\theta_{i,f,ph}$ are expressed as following:

$$\cos\theta_i = \cos\theta_e \cos\theta + \sin\theta_e \sin\theta \cdot \cos(\varphi - \varphi_e);$$
$$\cos(\theta_f) = \cos\theta_e \cos\theta' + \sin\theta_e \sin\theta' \cdot \cos(\varphi' - \varphi_e);$$
$$\cos(\theta_{ph}) = \cos\theta \cos\theta' + \sin\theta' \sin\theta \cdot \cos(\varphi - \varphi').$$

where index {e} used for initial electron and {'} for scattered photon. For the most interesting case of "head-to-head" collision

$$\bar{\mathbf{p}}\vec{k} = -p\omega, \quad \theta_i = \pi; \ \theta = \theta_f = \pi - \theta_{ph}$$

the energy of scattered photons $\hbar\omega'$ depends only on scattering angle θ:

$$\hbar\omega' = \hbar\omega \cdot \frac{\mathrm{E} + \mathrm{p}c}{\mathrm{E} + \hbar\omega - (\mathrm{p}c - \hbar\omega)\cdot\cos\theta} = \hbar\omega \cdot \frac{1+\beta}{1 + r - (\beta - r)\cdot\cos\theta}; \quad r = \frac{\hbar\omega}{\mathrm{E}}. \tag{11}$$

The parameter $r = \hbar\omega / \mathrm{E} = R / [2\gamma^2(1+\beta)]$ is caused by recoil and it "starts to play" when energy of scattered photons $\hbar\omega'$ is comparable with electron energy E. It also limits maximum energy of scattered photons (see Introduction, Eq. (5)).

2.2 The cross-section.

Compton scattering is a standard process in Classical Relativistic Quantum Theory (QED) and represented by Feyman's diagrams shown on Fig. 8 (see for example [9]) .

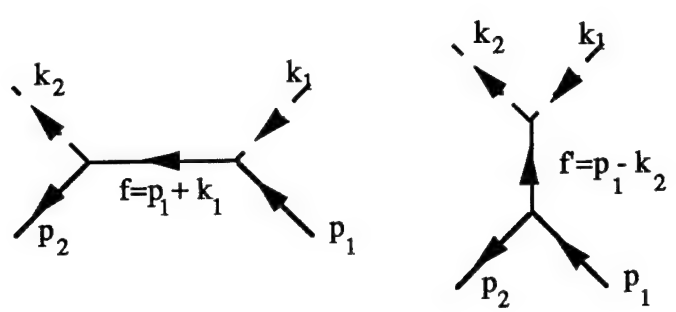

Fig. 8 Feynman diagrams for Compton scattering [9]: $p_{1,2}$ represent an electron, $k_{1,2}$ represent a photon.

Formulae for cross-section use kinematics invariants. In term of 4-vectors three dependent kinematics invariants are:

$$s = (p+k)^2 = (p'+k')^2 = m^2 + 2pk = m^2 + 2p'k';$$
$$t = (p-p')^2 = (k-k')^2 = 2(m^2 - pp') = -2kk'; \qquad s + t + u = 2m^2;$$
$$u = (p-k')^2 = (p'-k)^2 = m^2 - 2pk' = m^2 - 2p'k;$$

$$x = \frac{s - m^2}{m^2}; \quad y = \frac{m^2 - u}{m^2}. \tag{12)}$$

These expressions can be used in arbitrary frame. In the lab-frame expressions for (13) become:

$$x = \frac{2pk}{m^2} = \frac{2(\mathrm{E}\hbar\omega - \vec{p}\vec{k})}{mc^2} = \frac{2\gamma\hbar\omega(1-\beta\cos\theta_i)}{mc^2}; \; y = \frac{2pk'}{m^2} = \frac{2(\mathrm{E}\hbar\omega' - \vec{p}\vec{k}')}{mc^2} = \frac{2\gamma\hbar\omega'(1-\beta\cos\theta_f)}{mc^2}. \tag{13}$$

For fixed energy of electrons and optical photons ($s = const$) the cross-section can be expressed through x, y, dy. Cross-section depends on polarization of photons and electrons. We can assume in most cases that electrons in the storage ring are not polarized, because polarization time is few hours and a special precautions required to produce polarized electrons. Therefore, we will discuss only unpolarized electrons.

The differential cross-section for unpolarized electron and photons is:

$$d\overline{\sigma} = \frac{8\pi r_e^2}{x^2} dy \left\{ \left(\frac{1}{x} - \frac{1}{y}\right)^2 + \left(\frac{1}{x} - \frac{1}{y}\right) + \frac{1}{4}\left(\frac{x}{y} + \frac{y}{x}\right) \right\}; \tag{14}$$

where r_e is the classical radius of electron. In electron rest frame ($\bar{p} = 0$) this gives the classical Klein-Nishina formula:

$$d\overline{\sigma} = \frac{r_e^2}{2}\left(\frac{\omega'}{\omega}\right)^2 \left\{ \frac{\omega}{\omega'} + \frac{\omega'}{\omega} - \sin^2\theta \right\} do'.$$

Total cross-section is [9]:

$$\overline{\sigma}_{tot} = \frac{8\pi r_e^2}{x^2} \int_{x/(x+1)}^{x} dy \left\{ \left(\frac{1}{x} - \frac{1}{y}\right)^2 + \left(\frac{1}{x} - \frac{1}{y}\right) + \frac{1}{4}\left(\frac{x}{y} + \frac{y}{x}\right) \right\} = \frac{2\pi r_e^2}{x} \left\{ \left(1 - \frac{4}{x} - \frac{8}{x^2}\right)\ln(1+x) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(1+x)^2} \right\}. \tag{15}$$

For low energy case ($x \ll 1$, as for the Duke project) the cross-section is only slightly different from classical Thompson formula $\sigma_{Th} = \frac{8\pi r_e^2}{3}$:

$$\overline{\sigma}_{tot} \cong \frac{8\pi r_e^2}{3}(1 - x); \tag{16}$$

while it is very different in high energy case ($x \gg 1$):

$$\overline{\sigma}_{tot} \cong \frac{2\pi r_e^2}{x}\left(\ln x + \frac{1}{2}\right).$$

2.3 Polarization effects.

For polarized initial and scattered photons and unpolarized electrons, the cross-section is:

$$d\sigma = \frac{d\bar{\sigma}}{2} + \frac{2r_e^2 d\varphi dy}{x^2} \cdot \begin{Bmatrix} -(\xi_3+\xi_3')\left[\left(\frac{1}{x}-\frac{1}{y}\right)^2+\left(\frac{1}{x}-\frac{1}{y}\right)\right]+\xi_1\xi_1'\left(\frac{1}{x}-\frac{1}{y}+\frac{1}{2}\right)+ \\ +\frac{\xi_2\xi_2'}{2}\left(\frac{x}{y}+\frac{y}{x}\right)\left(\frac{1}{x}-\frac{1}{y}+\frac{1}{2}\right)+\xi_3\xi_3'\left[\left(\frac{1}{x}-\frac{1}{y}\right)^2+\left(\frac{1}{x}-\frac{1}{y}\right)+\frac{1}{2}\right] \end{Bmatrix}; \tag{17}$$

where $d\bar{\sigma}$ is given by (14), φ is azimuthal angle and $\bar{\xi} = (\xi_1, \xi_2, \xi_3); \bar{\xi}' = \left(-\xi_1', -\xi_2', \xi_3'\right)$ are the Stokes parameters of initial and final photons. The polarization matrix can be expressed in terms of the Stokes parameters:

$$\rho_{ik} = \frac{\langle \mathrm{E}_{oi}\mathrm{E}^*_{ok}\rangle}{\sum_j \langle \mathrm{E}_{oj}\mathrm{E}^*_{oj}\rangle} = \frac{1}{2}\begin{bmatrix} 1+\xi_3 & \xi_1 - i\xi_2 \\ \xi_1 + i\xi_2 & 1-\xi_3 \end{bmatrix}.$$

$\xi_3 = 1$ means horizontal (x) linear polarization, and $\xi_3 = -1$ means vertical (y) linear polarization. ξ_1 described 45^{o} linear polarization in the same manner. ξ_2 characterizes circular polarization. Parameters $l = \sqrt{\xi_1^2 + \xi_3^2}$ and $C = \xi_2$ are Lorentz invariants. Factor $\frac{1}{2}$ in Eq. (17) indicates that we do not sum on the polarization of final photons $\bar{\xi}'$.

The most energetic scattered photons propagate along z axis (θ=0). For horizontally polarized initial photons, the ratio between number of vertically polarized and horizontally polarized final photons is defined by recoil parameter:

$$\frac{d\sigma_\perp}{d\sigma_{II}}(\theta=0) = \frac{R^2(1+R)}{(2+R)^2(1+R)+4R(1+2R)}.$$

The summation on the polarization of final photons ($\overline{\xi'} = 0$ and doubling of other terms) yields a simpler expression for the cross-section:

$$d\sigma = d\bar{\sigma} - \frac{4r_e^2 d\varphi dy}{x^2}\xi_3\left[\left(\frac{1}{x}-\frac{1}{y}\right)^2+\left(\frac{1}{x}-\frac{1}{y}\right)\right]; \tag{18}$$

which depends only on linear polarization ξ_3 of initial photon. It is essential to mention, that ξ_3 depends on plane of photon scattering : $\xi_3 = 1$ when electric field of optical photon is perpendicular to plane of photon scattering. Thus, $\xi_3 = \cos 2\varphi$. The parameters x, y do not depend on φ and integration on φ bring us back to Eq. (14).

We are interested in the case of "head-to-head" collision $\theta_i = \pi$. We express all parameters through angle of final photon θ in the lab frame using Eq. (13):

$$x = 2\gamma(1+\beta)\cdot\frac{\hbar\omega}{mc^2};\ y = 2\gamma(1-\beta\cos\theta)\cdot\frac{\hbar\omega'}{mc^2};$$

$$dy = d\left(2\gamma(1-\beta\cos\theta)\cdot\frac{\hbar\omega'(\theta)}{mc^2}\right) = \frac{2(1+\beta)^2(\hbar\omega)^2}{\left(1+r-(\beta-r)\cdot\cos\theta\right)^2 m^2c^4}\cdot\sin\theta d\theta = 2\cdot\left(\frac{\hbar\omega'}{mc^2}\right)^2\sin\theta d\theta.$$

Taking into account definition of solid angle $do' = \sin\theta d\theta d\varphi$) we can rewrite formula (18) in new form:

$$d\sigma = \frac{8r_e^2}{x^2}\left\{\frac{1}{4}\left(\frac{x}{y}+\frac{y}{x}\right)+(1-\xi_3)\left[\left(\frac{1}{x}-\frac{1}{y}\right)^2+\left(\frac{1}{x}-\frac{1}{y}\right)\right]\right\}\cdot\left(\frac{\hbar\omega'}{mc^2}\right)^2 do'. \tag{19}$$

which gives angular distribution of γ-rays for both linear ($\xi_3 = \cos 2\varphi$) and circular ($\xi_3 = 0$) polarization of initial photons. It is obvious from Eq. (18) that for circular polarized of initial photons the total (averaged on polarization) distribution of final photons has the cross-section and azimuthal symmetry the same as those for unpolarized initial photons. Linear polarization of initial photons creates azimuthal modulation of the cross-section with the same differential cross-section in $d\theta$ as for unpolarized initial photons. In other words: (1) there are the same number of final photons in solid angle or energy interval for all possible polarization of initial photon; (2) in the case of linear polarized initial photon, the final photons are redistributed φ-wise. Fig. 9 shows distributions of γ-rays for circular and linear polarization of initial photon at the target located at 40 meters from collision point for the Duke source operation 12 eV FEL at 1 GeV.

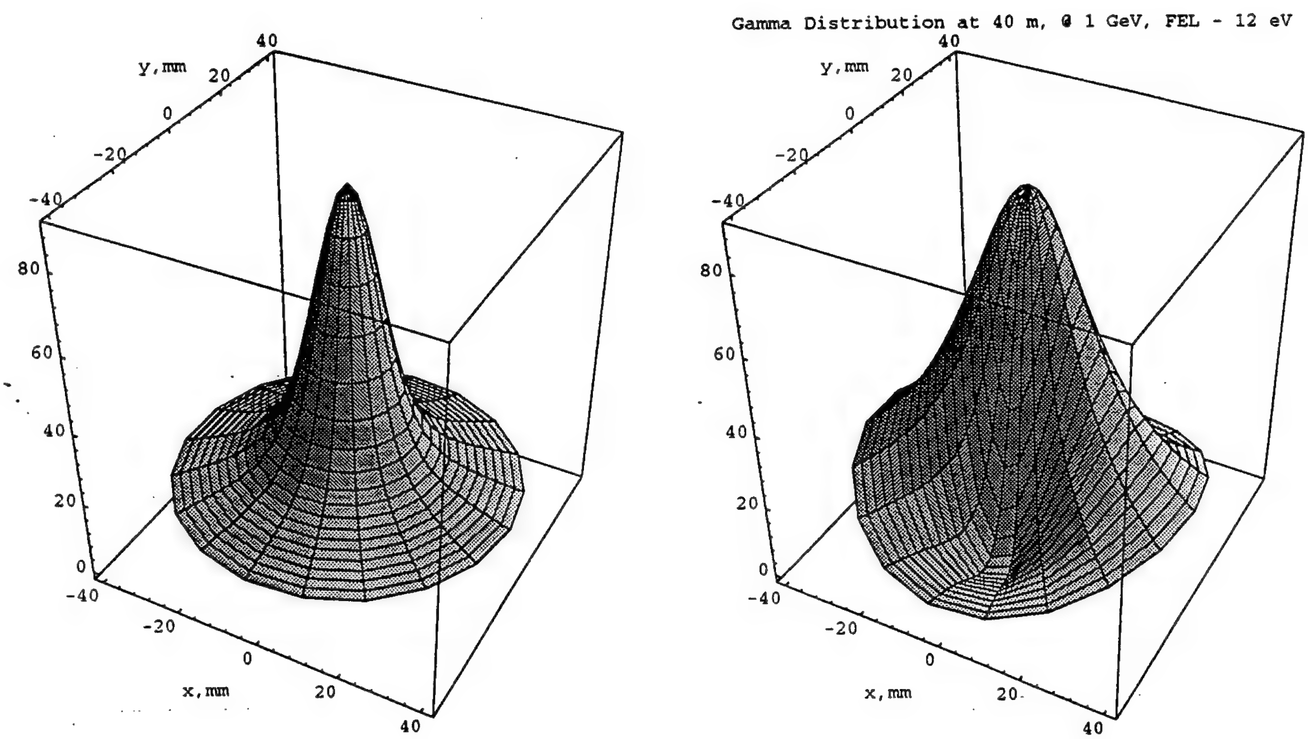

Fig. 9 The distributions of γ-rays for circular (left) and linear polarization (right) of 12 eV initial photon at the target located at 40 meters from collision point for the Duke source at 1 GeV.

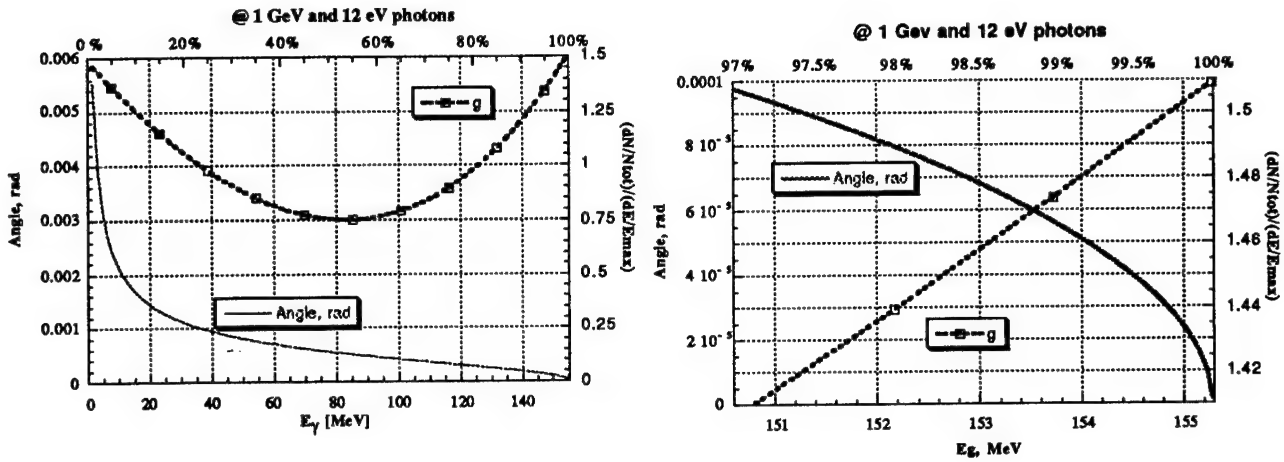

Fig. 10 The γ-ray energy distribution function $g(\rho,x)$ and observation angle for 12 eV initial photons and 1 GeV electrons. Full range plot $\rho = E_\gamma / E_{\gamma\max} = [0\%,100\%]$, $E_{\gamma\max} = 155.28\,MeV$ is on the left; the high energy edge $\rho = [97\%,100\%]$ is on the right. The solid curve shows observation angle; the dashed curve is partition function $g(\rho,x)$.

2.4 Energy distribution of scattered photons.

The energy of the scattered photon (gamma), as shown by Eq. (10,11), depends on parameters of initial electron and photon and scattering angle θ but not on azimuthal angle φ. Typical dependence of scattered photon energy on scattering angle θ for the Duke source is shown on Fig. 10. The cross-section integrated on φ can be expressed in terms of scattered photon energy. We consider here most interesting case of head-to-head collision. Formulae can be easily modified for other cases.

Using Eqs. (11) and (12) we can express all parameters appearing in Eq. (14) through the energies of initial electron, initial photon and final photon. It is natural to normalize cross-section per energy interval of final photons:

$$\frac{d(\hbar\omega')}{(\hbar\omega')_{\max}};\ (\hbar\omega')_{\max} = \hbar\omega\cdot\frac{\mathrm{E}(1+\beta)}{\mathrm{E}(1-\beta)+2\hbar\omega} = 4\gamma^2\hbar\omega\cdot\frac{(1+\beta)^2}{4(1+2\gamma^2 r(1+\beta))},$$

i.e. maximal energy final photons $E_{\gamma\max} = (\hbar\omega')_{\max}$ who propagate z axis (θ=0). Using of following ratios:

$$x = \frac{2\mathrm{E}(1+\beta)\hbar\omega}{(mc^2)^2};\quad y = x\frac{\beta\mathrm{E}-\hbar\omega'}{\beta\mathrm{E}-\hbar\omega};\ dy = -x\frac{d(\hbar\omega')}{\beta\mathrm{E}-\hbar\omega}.$$

the energy distribution is can be rewritten as :

$$d\overline{\sigma}_{en} = \frac{8\pi r_e^2}{x}\left\{\left(\frac{1}{x}-\frac{1}{y}\right)^2 + \left(\frac{1}{x}-\frac{1}{y}\right) + \frac{1}{4}\left(\frac{x}{y}+\frac{y}{x}\right)\right\}\frac{\hbar\omega\cdot\mathrm{E}(1+\beta)}{(\beta\mathrm{E}-\hbar\omega)(\mathrm{E}(1-\beta)+2\hbar\omega)}\cdot d\left(\frac{\omega'}{\omega'_{\max}}\right). \tag{20}$$

$$d\overline{\sigma}_{en} = \frac{8\pi r_e^2}{x}\left\{\left(\frac{1}{x}-\frac{1}{y}\right)^2 + \left(\frac{1}{x}-\frac{1}{y}\right) + \frac{1}{4}\left(\frac{x}{y}+\frac{y}{x}\right)\right\}\frac{r(1+\beta)}{(\beta-r)(1-\beta+2r)}\cdot d\left(\frac{\omega'}{\omega'_{\max}}\right)$$

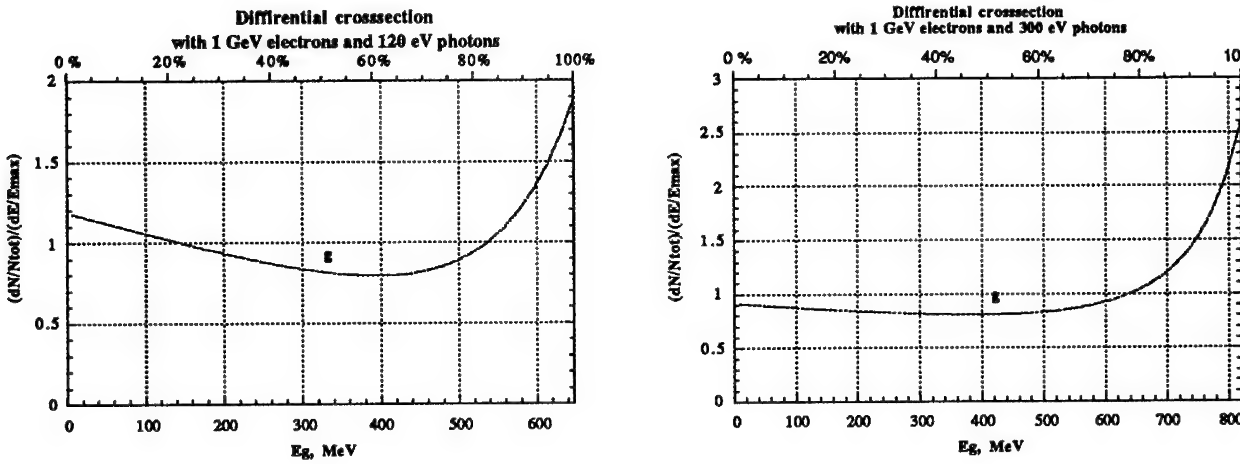

Fig. 11 The γ-ray energy distribution function $g(\rho,x)$ for 1 GeV electrons and
a) 120 eV initial photons ($E_{\gamma\max} = 647.67\,MeV$, left), b) 300 eV initial photons ($E_{\gamma\max} = 821.29\,MeV$, right).
Increase of the relative number of high energy γ-rays caused by recoil. The use of OK-4 spontaneous radiation is assumed.

This formula gives energy distribution of final photons into unit interval in term of their maximum energy. Integrated over full energy interval $\{E_{\gamma\min} / E_{\gamma\max}, 1\} = \{\omega / \omega_{\max}, 1\}$ is gives us the total cross-section (15). It is useful to rewrite (20) in dimensionless:

$$\frac{d\overline{\sigma}_{en}}{\overline{\sigma}_{tot}} = g(\rho,x)\cdot d\rho; \quad \rho = \frac{\omega'}{\omega'_{\max}} = \frac{E_\gamma}{E_{\gamma\max}}; \tag{21}$$

where $g(\rho,x)$ is simple combination of Eq. (20) and (15), and x stand for parameters of initial particles. The meaning of $g(\rho,x)$ is simple: it gives portion of total flux (number) of scattered photons with energy E_γ into unit interval of relative energy:

$$\Delta N = N_{tot}\, g\left(\frac{E_\gamma}{E_{\gamma\max}}, x\right)\frac{\Delta E_\gamma}{E_{\gamma\max}}. \tag{22}$$

Typical graphs of $g(\rho,x)$ are shown in Fig.10 for low energy case and Fig.11 for high energy cases. When recoil is small, $g(\rho,x)$ has maximum of 1.5 at maximum energy. The potion of γ-rays in the central cone with desirable energy spread can be estimated as:

$$\Delta N \cong 1.5 N_{tot} \frac{\Delta E_\gamma}{E_{\gamma\max}}. \tag{23}$$

This value grow up with increasing of the recoil which causes relative increase of high energy γ-rays. It is possible to use collimation of γ-rays to achieve desirable energy resolution. The schematic of this is shown on Fig. 12: A cylindrical collimator with radius a , located at a distance L, will cut a central cone of γ-rays and top slice of their energy distribution.

However, energy resolution could be influenced by properties of electron beam as we would see later.

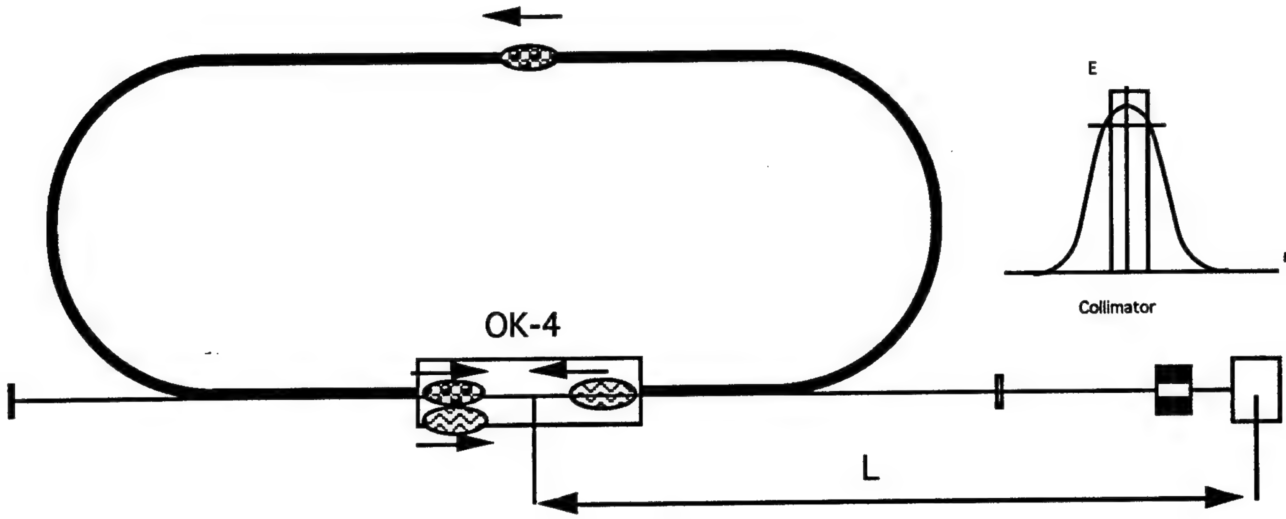

Fig.12 Schematic of high energy resolution γ-ray spectroscopy on the Duke storage ring.

2.5 Number of scattered photons.

In our case each electron is fully described by its momentum $\vec{p}$:

$$\mathrm{E} = c\sqrt{m^2c^2 + \vec{p}^2};\ \vec{v}_e = \vec{p}c / \sqrt{m^2c^2 + \vec{p}^2};$$

and photon is fully described by its wavevector $\vec{k}$:

$$\omega = c|\vec{k}|;\ \vec{v}_{ph} = c\vec{k} / |\vec{k}|.$$

By definition (see Ref. [8], §12), a number of events occurred in volume dV in time dt is

$$d\nu = \sigma \cdot |\vec{v}_1 - \vec{v}_2| n_1 n_2 dVdt;$$

where σ is cross-sections of the processes under consideration, $n_{1,2}$ are particles densities and $\vec{v}_{1,2}$ are particles velocities. The cross-section σ depends on the process under consideration (see Sections 2.2-2.3) and conditions ($\aleph$ = what result and where it is observed, $\aleph$), parameters of initial particles and there momenta: $\sigma = \sigma_\aleph(\vec{p}_1, \vec{p}_2)$. The conditions $\aleph$ can be very simple as "all results everywhere", or can be complex.

For example, in the case of inverse Compton scattering, the information on density and energy distribution of the final photons (γ-rays) distribution on a target/detector is very critical. This conditions can be state as following: 1) γ-ray generated by electron-photon collision at point $\vec{r}$ in space must reach point $\vec{r}_t$; 2) γ-ray energy must be E_γ. First condition gives us direction of final photon propagation:

$$\frac{\vec{k}'}{|\vec{k}'|} = \frac{\vec{r}_t - \vec{r}}{|\vec{r}_t - \vec{r}|}; \tag{24.1}$$

which define all angles $\theta_i, \theta_{ph}, \theta_f, \varphi$ of scattering (see Section 2.1) and which should be plugged into equations:

$$\cos\theta_i = \frac{\vec{k}\vec{p}}{|\vec{k}|\cdot|\vec{p}|};\cos\theta_{ph} = \frac{\vec{k}\vec{k}'}{|\vec{k}|\cdot|\vec{k}'|};\cos\theta_f = \frac{\vec{p}\vec{k}'}{|\vec{p}|\cdot|\vec{k}'|}.$$

The requirement to have energy of E_γ should be presented as multiplicative factor:

$$\delta\left(\frac{\hbar\omega\cdot(\mathrm{E}-\mathrm{pc}\cdot\cos\theta_i)}{\mathrm{E}+\hbar\omega-\mathrm{pc}\cdot\cos\theta_f-\hbar\omega\cdot\cos\theta_{ph}}-E_\gamma\right); \tag{24.2}$$

where $\delta(x)$ id Dirac δ–function (see [8], p.70). Therefore, the $\sigma_\aleph$ for these conditions is one of the cross-sections from Sections 2.2-2.3 with angles defined from geometry (as above) and multiplies by energy δ–function. If the conditions can not be satisfied, cross-section is equal zero.

By the way, Eq. (20) can be derived from Eq. (14) or Eq. (19) by multiplication by energy δ–function and integration. Further in this section we assume that conditions $\aleph$ are arbitrary.

Let's consider electron bunch and beam of initial photons described by their distribution functions $f_e(\vec{r},\vec{p},t)$ and $f_{ph}(\vec{r},\vec{k},t)$ in the phase space. The distribution functions are considered to be normalized

$$\int f_e(\vec{r},\vec{p},t)d\vec{p}^3dV = 1;\ \int f_{ph}(\vec{r},\vec{k},t)d\vec{k}^3dV = 1.$$

The density of electrons with momentum $\vec{p}$ and photons with wavevector $\vec{k}$ are:

$$n_e = N_e f_e(\vec{r},\vec{p},t)d\vec{p}^3;\ n_{ph} = N_{ph} f_{ph}(\vec{r},\vec{k},t)d\vec{k}^3;$$

where N_e is total number of electron in the beam, N_{ph} is total number of photons in the beam. The relative velocity in the lab frame is

$$|\vec{v}_e-\vec{v}_{ph}| = c\left|1-\frac{\vec{p}\vec{k}}{|\vec{k}|\sqrt{m^2c^2+\vec{p}^2}}\right| = c\left|1-\frac{\vec{p}\vec{n}c}{\mathrm{E}}\right| = c|1-\beta\cos(\theta_i)|.$$

Cross-sections of Compton scattering are described in previous section. Therefore, the number of scattered photons appearing in volume dV in time dt is:

$$d\nu = N_e N_{ph}\sigma_\aleph(\vec{p},\vec{k})\cdot\left|1-\frac{\vec{p}\vec{k}}{|\vec{k}|\sqrt{m^2c^2+\vec{p}^2}}\right| f_e(\vec{r},\vec{p},t)f_{ph}(\vec{r},\vec{k},t)d\vec{p}^3d\vec{k}^3\,dVcdt.$$

The instantaneous rate of scattered photons $\dot{\nu}$ could be found by integration over $d\vec{p}^3d\vec{k}^3\,dV$ and total number per collision (for finite duration of both electron and photon bunches) is:

$$\nu_{collision} = \int\dot{\nu}\,dt = N_e N_{ph} c\iiint d\vec{p}^3 d\vec{k}^3\,dVdt\cdot\sigma_\aleph(\vec{p},\vec{k})\cdot\left|1-\frac{\vec{p}\vec{k}}{|\vec{k}|\sqrt{m^2c^2+\vec{p}^2}}\right| f_e(\vec{r},\vec{p},t)f_{ph}(\vec{r},\vec{k},t). \tag{25}$$

If collisions occur with periodically with frequency f_{col}, the total rate of scattered photons is:

$$\dot{N} = f_{col} \cdot V_{collision}.$$

In some cases, when the conditions $\aleph$ do not link spatial coordinates and cross-section ($\partial_{\vec{r}}\sigma_{\aleph}(\vec{p}_1, \vec{p}_2) \equiv 0$) and the distribution functions can be also factored :

$$f_e(\vec{r},\vec{p},t) = f_{es\vec{p}}(\vec{r},t) f_{em}(\vec{p}); \; f_{ph}(\vec{r},\vec{k},t) = f_{phs\vec{k}}(\vec{r},t) f_{phm}(\vec{k});$$

Eq. (25) can be reduced to following form:

$$V_{collision} = N_e N_{ph} \int d\vec{p}^3 d\vec{k}^3 f_{em}(\vec{p}) f_{phm}(\vec{k}) \frac{\sigma_{\aleph}(\vec{p},\vec{k})}{A(\vec{p},\vec{k})}; \;\; A(\vec{p},\vec{k}) = \left\{ \frac{c}{|1-\beta\cos(\theta_i)|} \int dtdV f_{es\vec{p}}(\vec{r},t) f_{phs\vec{k}}(\vec{r},t) \right\}^{-1} \qquad (26)$$

where $A(\vec{p},\vec{k})$ is effective area containing particles with $(\vec{p},\vec{k})$. For head-to-head collision of monoenergetic ultrarelativistic electrons $\beta \cong 1$ and monochromatic photons Eq.(22) looks very simple:

$$V_{collision} = \frac{N_e N_{ph} \sigma_{\aleph}(p,k)}{A}; \qquad A = \frac{1}{2c\iint dVdt \cdot f_e(\vec{r},t) f_{ph}(\vec{r},t)}.$$

Therefore, knowledge of cross-section, conditions and distribution functions allow to calculate all parameters of scattered photons: their rate, time structure, energy and space distributions, etc.

3. THE DUKE GAMMA-SOURCE.

The formulae derived in previous chapter do not use approximation and can be used to study influence of different parameters on the properties of the ICS source. Nevertheless, effect of some parameters can be many orders of magnitude lower as compared with others. For example, for 1 GeV electrons in the Duke storage ring $\beta = v/c \cong 1 - 1.3 \cdot 10^{-7}$ and should be taken into account in expressions containing $1-\beta$, while using $1+\beta \cong 2$. Also, the angular spread of electrons and initial photons is much less then 1 mrad. Thus, one can use $1+\beta \cdot \cos(\theta_i) \cong 2$, dropping effects $\sim 10^{-7}$.

Main parameters of the Duke storage ring and OK-4 FEL are summarized in Table I and Table II. Additional parameters will be described in the text.

3.1 Distribution functions of electron beam and initial photons.

The paraxial distribution functions of electron bunches in storage ring and distribution of FEL (initial) photons are well defined [7]. The electron bunch propagating in free space along z-axis has the distribution function of:

$$f_e(\vec{r},\vec{p},t) = \frac{1}{(2\pi)^3 \varepsilon_x \varepsilon_y \sigma_p \sigma_l} \exp\left\{ -\frac{1}{2}\left(\frac{(x-x'z)^2 + (\beta_x x')^2}{\beta_x \varepsilon_x} + \frac{(y-y'z)^2 + (\beta_y y')^2}{\beta_y \varepsilon_y} + \frac{(p_z - p_o)^2}{\sigma_p^2} + \frac{(z-ct)^2}{\sigma_l^2} \right) \right\};$$

where $\bar{p} = p_z(\hat{e}_z + \hat{e}_x x' + \hat{e}_y y')$; β_x, β_y are values of β-function in crossover point assumed to be at z=0; $\varepsilon_x, \varepsilon_y$ are transverse emittances σ_p, σ_l are momentum spread and the bunch length of the e-beam. The distribution of the initial photons in FELs looks very similar (we assumed FEL TEM_{00} mode with waist at z=0 and photons propagating in opposite direction):

$$f_{ph}(\vec{r},\vec{k},t) = \frac{k^2}{2\pi^3\sigma_k\sigma_z}\exp\left\{-k\left(\frac{(x-\vartheta_x z)^2 + (\beta_o\vartheta_x)^2 + (y-\vartheta_y z)^2 + (\beta_o\vartheta_y)^2}{\beta_o}\right) - \frac{1}{2}\left(\frac{(k-k_o)^2}{\sigma_k^2} + \frac{(z+ct)^2}{\sigma_z^2}\right)\right\};$$

where $\vec{k} = k(\hat{e}_z + \hat{e}_x\vartheta_x + \hat{e}_y\vartheta_y)$; β_o is the Rayleigh length, σ_k, σ_z are wavevector spread and the photon bunch length. For proposed Duke project $\beta_x = \beta_y = \beta_o = 4m$.

It quite evident that time profile of γ-ray pulse would be close to Gaussian pulse with $\sigma_t \cong \sqrt{\sigma_l^2 + \sigma_z^2}/2c$. The lengths of the electron and FEL bunches is much smaller then the waist length and angular spread of the beam does not affect beam overlap A:

$$A = \frac{\lambda\beta_o}{2}\sqrt{1 + \frac{4\pi\beta_x\varepsilon_x}{\lambda\beta_o}}\sqrt{1 + \frac{4\pi\beta_y\varepsilon_y}{\lambda\beta_o}}; \ \lambda = \frac{2\pi}{k}. \tag{26}$$

For at 1 GeV e-beam and λ=100 nm FEL beam (12 eV), A = 0.37 mm^2.

3.2 Flux of γ-rays.

Total number of scattered photons per collision is proportional to the total cross-section (15) divided by effective overlap area and product of number of electrons and photons:

$$N_\gamma = \frac{\sigma_{tot}}{A} N_e N_{ph}.$$

The flux, number of scattered photons per second, is simple product of N_γ and frequency of collisions. For one FEL bunch and one electron (target) bunch this is the revolution frequency $F=f_o= 2.7898\ 10^6$ 1/sec. For multibunch operation it is $F=N_b f_o$, where N_b is number of colliding bunches. It is important to note that in multibunch case there could be additional collision points. All following calculation were done for one FEL bunch and one electron (target) bunch. Second electron bunch is assumed to be used for FEL only. In this case, we can use flux of FEL photons $\dot{N}_{ph} = f_o N_{ph}$, plotted on Fig. 6. The number of electrons in target bunch is defined by bunch current I_e: $N_e = I_e / f_o / e = 2.238\cdot 10^{12}\cdot I_e[A]$; $e = 1.602\cdot 10^{-19} C$. Therefore, total flux can be easily calculated using Eq. (15):

$$\dot{N}_\gamma = \frac{\sigma_{tot}}{A} 2.238\cdot 10^{12}\cdot I_e[A]\cdot \dot{N}_{ph}.$$

Fig. 12 shows typical fluxes of γ-rays for two values of target bunch current as function of maximum energy of γ-rays: energy of storage ring and FEL wave length are tuned to required values to produce $E_{\gamma max}$.

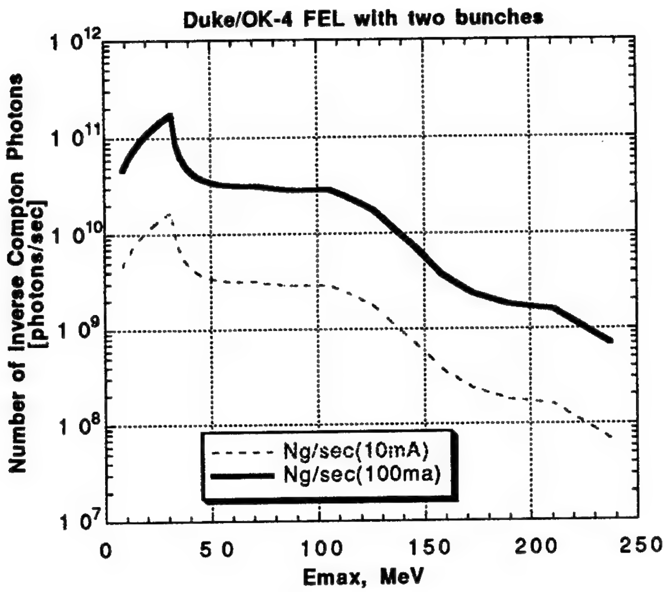

Fig. 12 The γ-ray flux from OK-4/Duke source as function of cut-off energy $E_{\gamma max}$ for 10 mA and 100 mA target bunches.

Desirable energy of γ-ray can be chosen by appropriate tuning of the OK-4 FEL and storage ring energy. Using a collimator, one can chose a desirable energy resolution. To optimize flux with chosen energy resolution, the collimator should be placed at the center of the γ-ray cone ($\theta = 0$, see Figs. 9-11).The flux through the collimator is a portion of the total flux defined by Eqs. (20-22). It can be always estimated by as 1.5 of total flux times energy resolution.

For example, a) an experiment required 30 MeV γ-ray with 1% full energy spread (± 0.15 MeV) can utilize 1.5% of the total flux ($2.4 \cdot 10^8$ γ/sec at 10 mA and $2.4 \cdot 10^9$ γ/sec at 100 mA); b) an experiment required 150 MeV γ-ray with 3% full energy spread (± 2.25 MeV) can use 4.5% of the total flux ($4.2 \cdot 10^7$ γ/sec at 10 mA and $4.2 \cdot 10^8$ γ/sec at 100 mA). These fluxes are few orders of magnitude higher then what available now in this energy range.

It is important to notice, γ-ray energy defined by observation angle if electron beam does not have angular and energy spread. There is fundamental limit of the γ-rays energy spread defined by beam quality. Sub-mrad divergence of electron and optical (initial photon) beams do not effect flux of γ-rays (total or through the collimator), but it effects local (at chosen observation angle) energy distribution of γ-rays.

3.3 Energy resolution of γ-rays.

Formula (25) is very general and can be used (together with other formulae from Chapter 2) to calculate all parameters of γ-ray beam, including flux, central energy, RMS energy spread, polarization etc. It should be used for specific experimental set-up. To avoid pages of formulae, we consider here only the critical issue of ultimate energy resolution and discuss its dependence on beam parameters.

Fig. 13 shows sketch (beam size is sub-mm, distance to the collimator is L = 40 m for the Duke project) of collimated γ-ray beam production. Small portion of γ-rays, satisfying following conditions (see Eq. (24.1):

$$\vec{n} = \frac{\vec{k}'}{|\vec{k}'|} = \frac{\hat{e}_z L + \vec{\rho}}{\sqrt{L^2 + \vec{\rho}^2}}; \ \vec{\rho} = \hat{e}_x x + \hat{e}_y y;;$$

will propagate through the pin-hole collimator. Real geometry is paraxial ($\rho <<< L$; $\theta <<< 1$) which simplify all calculations. At first, solid angle of the collimator does not depend of particle position. Second, in the Duke case, $\theta << 1/\gamma$, and differential cross-section does not depend on θ.

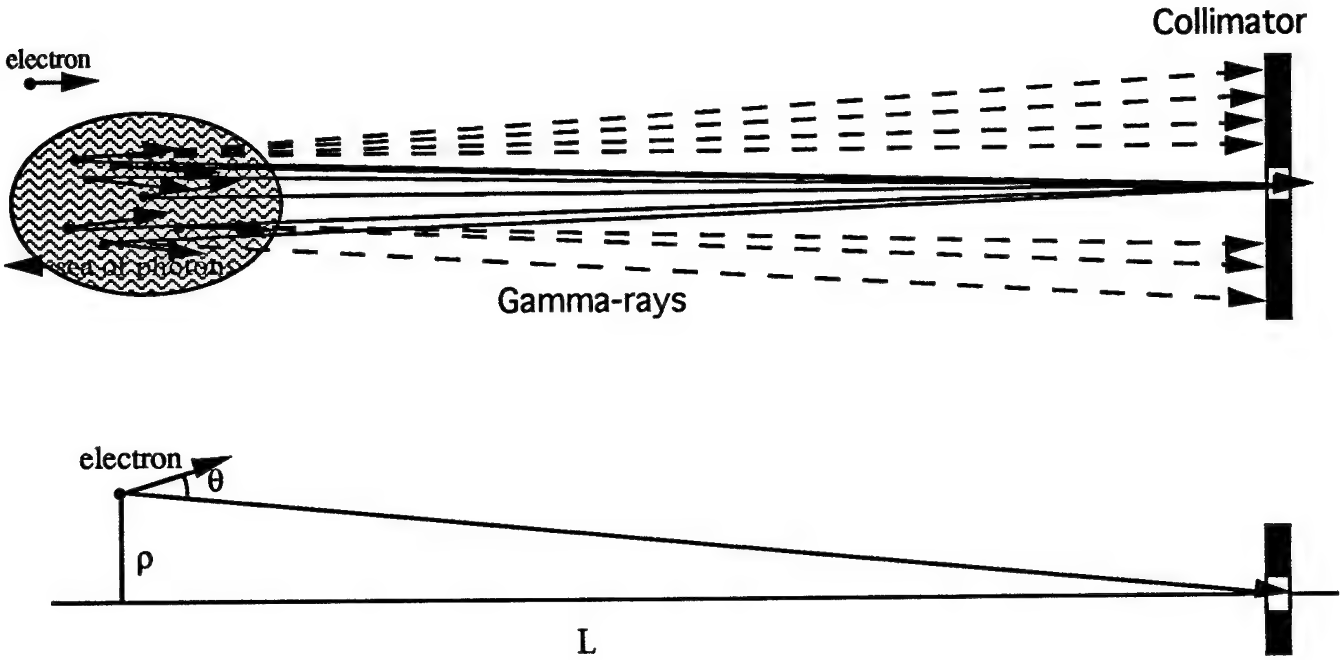

Fig. 13 Scheme of collimated γ-beam: electrons with some momentum and angular spread scatter the FEL photons into small cone (1 mrad) of γ-rays; a pin-hole collimator absorbs most of γ-rays (dashed) while some of them go through the pin -hole (solid lines).

Further we assume ultrarelativistic electrons ($\gamma >> 1$), small angles and initial photons with $\hbar\omega << \mathbf{E}$. Lets consider first influence of energy spread of initial photons and spread of θ_i using Eq. (10) for near "head-to-head" collision: $|\pi - \theta_i| << 1$. Simple calculations give:

$$\frac{\Delta\omega'}{\omega'} \cong \left\{1 - \frac{2\gamma^2\hbar\omega}{\left(1+(\gamma\theta_f)^2\right)\mathbf{E} + 2\gamma^2\hbar\omega}\right\}\frac{\Delta\omega}{\omega} - \frac{\theta^2{}_i}{4} \tag{27}$$

The energy (momentum) spread of electrons does not change the geometry and its contribution is:

$$\frac{\Delta\omega'}{\omega'} \cong 2\left\{1 - \frac{(\gamma\theta_f)^2 mc^2 + 2\gamma\hbar\omega}{\left(1+(\gamma\theta_f)^2\right)mc^2 + 4\gamma\hbar\omega}\right\}\frac{\Delta p}{p}; \tag{28}$$

which means that γ-rays energy spread is almost doubles electron energy spread. Influence of θ_f and θ_{ph} is described by:

$$\frac{\Delta\omega'}{\omega'} \cong -\frac{\gamma^2 mc^2}{\left(1+(\gamma\theta_f)^2\right)mc^2 + 4\gamma\hbar\omega}(\Delta(\theta_f)^2 + \frac{2\hbar\omega}{\gamma mc^2}\Delta(\theta_{ph})^2); \tag{29}$$

where second term is much smaller then first for $\hbar\omega << E = \gamma mc^2$. Now we have all necessary relations to calculate influence of electron beam and initial photon beam on γ-rays energy spectrum. First, influence of θ_i, θ_{ph} is usually negligible. For the Duke parameters $\langle \theta^2{}_i \rangle = (\varepsilon_x + \varepsilon_y + \lambda / 4\pi) / \beta_{x,y,o} < 10^{-8}$ and $\hbar\omega / E \sim 10^{-8} - 10^{-7}$. Second, it is very important to install collimator on z-axis to take advantage of $\Delta(\theta_f)^2$ dependence. Otherwise, the energy spread of γ-rays will depend linearly of the source size and electron angular spread. The FEL laser beam could be used as a natural pointer along the z-axis.

Taking into account previous discussion on θ_i, θ_{ph}, the paraxial geometry and ultra-relativism of electron, the energy of scattered photon (γ-ray) can be written in very simple form:

$$\hbar\omega' \cong \hbar\omega \cdot \frac{4\gamma^2}{1 + (\gamma\theta_f)^2 + 4\gamma\hbar\omega / mc^2}. \tag{30}$$

Angle θ_f is defined by location and momentum of the electron $\vec{p} = p_z(\hat{e}_z + \hat{e}_x x' + \hat{e}_y y')$ (se Eq.(24.1)):

$$\theta_f^2 = \theta_x^2 + \theta_y^2; \quad \theta_x \equiv x' + \frac{x}{L}; \quad \theta_y \equiv y' + \frac{y}{L};;$$

and δ-function from (24.2) $\delta(\hbar\omega' - E_\gamma)$, where $\hbar\omega'$ is defined by Eq. (30) and E_γ is independent variable. Therefore, plugging $\delta(\hbar\omega' - E_\gamma)$ and distribution functions (Sec.3.1) into Eq. (25) one can find γ-rays energy distribution after the collimator.

For short electron and optical pulses ($\sigma_{l,z} << \beta_{x,y,o}$), integration over z and t is trivial and gives $\pi\sigma_l\sigma_z / c$. The integration on angular distribution of initial photons ($\vartheta_{x,y}$)is simple (because nothing depends on it) and yields $\pi / \beta_o k$.

It is possible to use change variables to $\theta_{x,y}$ from x', y' and to integrate on x, y. This integration a little more tricky but do not represent technical difficulties. The result is:

$$\int \exp\left\{ -\frac{x^2 + (\beta_x x')^2}{2\beta_x \varepsilon_x} - \frac{y^2 + (\beta_y y')^2}{2\beta_y \varepsilon_y} - k\frac{x^2 + y^2}{\beta_o} \right\} dx dy dx' dy' = \frac{2\pi\sqrt{\beta_x \varepsilon_x \beta_y \varepsilon_y}}{\sqrt{\xi_x \xi_y}} \int \exp\left\{ -\frac{\theta_x{}^2}{2\sigma^2{}_{\theta_x}} - \frac{\theta_y{}^2}{2\sigma^2{}_{\theta_y}} \right\} d\theta_x d\theta_y;$$

where

$$\xi_{x,y} = 1 + \frac{4\pi\beta_{x,y}\varepsilon_{x,y}}{\beta_o \lambda} + \left(\frac{\beta_{x,y}}{L}\right)^2; \quad \sigma^2{}_{\theta_x,\theta_y} = \frac{\varepsilon_{x,y}}{\beta_{x,y}} \left(1 + \frac{4\pi\beta_{x,y}\varepsilon_{x,y}}{\beta_o \lambda} + \left(\frac{\beta_{x,y}}{L}\right)^2\right) \Big/ \left(1 + \frac{4\pi\beta_{x,y}\varepsilon_{x,y}}{\beta_o \lambda}\right).$$

Therefore, we can estimate γ-ray energy spread caused by finite source size and angular spread of electron beam using Eq.(29):

$$\frac{\sigma_{\hbar\omega'}}{\hbar\omega'_{\max}} \cong -\frac{\gamma^2 mc^2}{mc^2 + 4\gamma\hbar\omega} \left(\sigma^2{}_{\theta_x} + \sigma^2{}_{\theta_x}\right).$$

This value can be optimized by appropriate choice of $\beta_{x,y,o}$. It is obvious that reduction β_o to minimal possible value will improve energy spread and flux. Therefore, minimum of β_o will be limited by technical details such as optical resonator stability for FEL, etc. In the Duke case, $\beta_o = 4m$ is defined by FEL requirements. Typical dependence of $\gamma^2\sigma^2{}_{\theta_x}$ on value of β_x is shown on Fig. 14.

Angular spread accepted by collimator is going down with increase of β_x 1) because angular spread of electrons going down and 2) source size does not increase significantly (it always less then laser beam size). There is a draw-back: effective area of overlap is growing with β_x and flux is going down. It reasonable to use $\beta_x \sim L$.

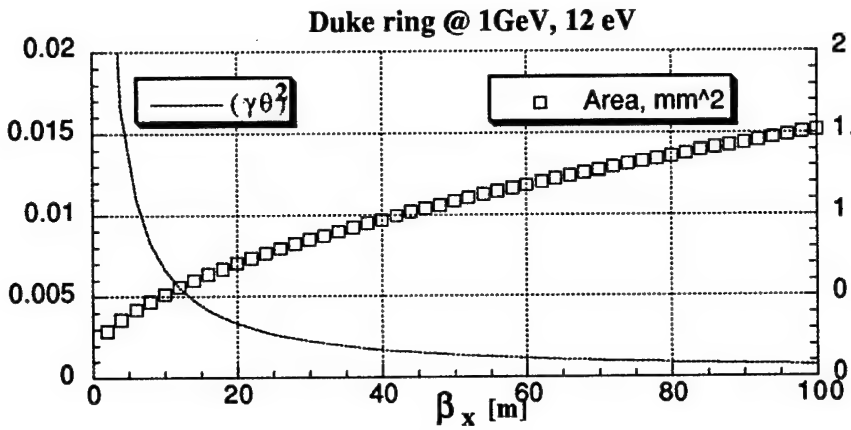

Fig. 14 Dependence of $\gamma^2\sigma^2{}_{\theta_x}$ and overlap area as function of horizontal β-function (L= 40m)

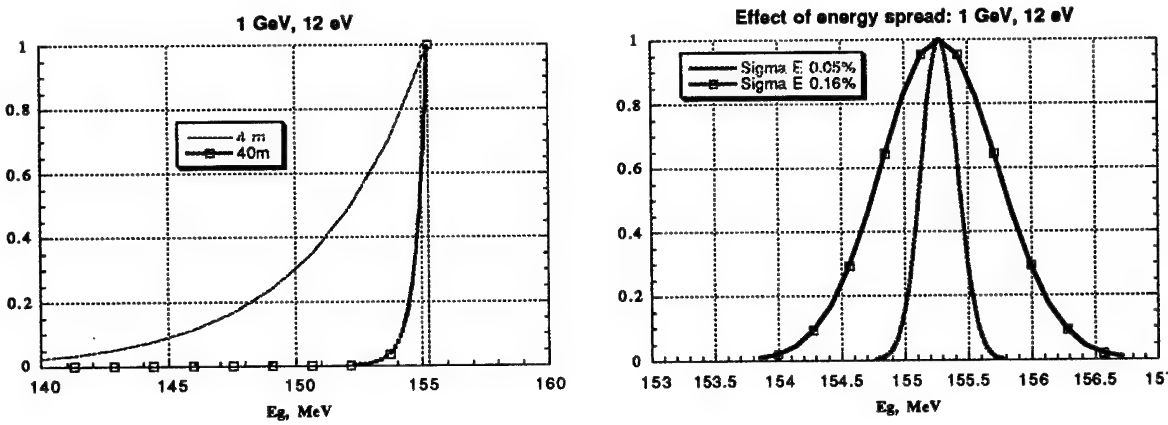

Fig. 15 Energy spectrum of γ-rays (normalized) after pin-hole collimator located at 40 m:
1) caused by emittance for β_x =4 m and 40 m (left) and 2) caused by energy spread of electrons (0.05% and 0.16%)

The γ-ray energy spread caused by vertical emittance is rather small (at 1 GeV, 12 eV: $\gamma^2\sigma^2_{\theta_y} \le 10^{-3}$; $\beta_y = 4m$, $\gamma^2\sigma^2_{\theta_y} \le 2\cdot10^{-4}$; $\beta_y = 40m$) and comparable with relative spread of initial photon energy $\sigma_\omega / \omega < 3\cdot10^{-4}$. Contribution of both this effects into γ-ray energy spread can be made even smaller ($<10^{-4}$) by reduction of coupling and FEL linewidth narrowing (see Table II)

Main contribution into γ-rays energy spread is caused by horizontal angular spread ($\gamma^2\sigma^2_{\theta_x} \approx 1.8\cdot10^{-2}$; $\beta_x = 4m$, at least 18 time larger then vertical, finite beam size contribution (β_x / L) is small for $\beta_x << L$) and electron beam energy spread $2\sigma_p / p \le 3\cdot10^{-3}$. Typical energy spectrum caused by horizontal emittance is shown on Fig. 15 (left) for two values of β_x, the effect of electron energy spread is shown on the same figure (right).

When effects of horizontal emittance and electron beam energy spread dominate (as for the Duke case), the integration on θ_y, k gives $\cong 2\pi\sigma_k\sigma_{\theta_y}$. We have left double integral, one of them can be evaluated analytically:

$$dN_\gamma(E_\gamma) = \frac{\gamma^2\hbar\omega}{\pi\sigma_\gamma\sigma_{eff}E_\gamma}\frac{dE_\gamma}{E_\gamma}dO\int_{\gamma\min}^{\infty}\frac{\sigma}{A}\cdot\exp\left\{-\frac{h}{2\gamma^2\sigma^2_{\theta_x}}-\frac{(\gamma-\gamma_o)^2}{2\sigma^2_\gamma}\right\}\frac{d\gamma}{\sqrt{h}};$$

where dO in solid angle of collimator, σ is Compton cross-section at zero angle (Eq. (19)) and other parameters are:

$$h = 4\frac{\gamma\hbar\omega}{mc^2}\frac{\gamma mc^2 - E_\gamma}{E_\gamma} - 1;\ \gamma_{\min} = \frac{E_\gamma}{2}\left(1+\sqrt{1+\frac{(mc^2)^2}{E_\gamma\hbar\omega}}\right);\ \sigma_{eff} = \gamma\sigma_{\theta_x}/\sqrt{\left(1+\frac{4\pi\beta_x\varepsilon_x}{\beta_o\lambda}\right)};\sigma_\gamma = \frac{\sigma_p}{mc}.$$

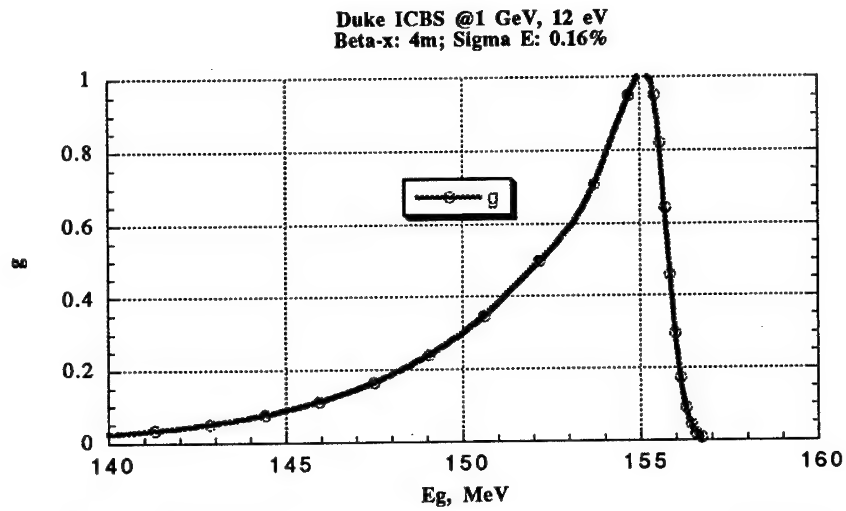

Fig. 16 Energy spectrum of γ-rays (normalized) after pin-hole collimator located at 40 m: β_x =4 m and $\sigma_p / p_o = 0.16\%$

Fig. 16 give the example of normalized spectrum using the above integral (for 100 mA beam with $\sigma_p / p_o = 0.16\%$). As was expected, the γ-ray spectrum is mostly defined by horizontal angular spread. The γ-rays have central energy of 152.057 MeV and RMS energy spread of 3.4 MeV. This worst case of the spectrum - it improves for lower currents and for lower energy of the electrons ($\gamma^2\theta_x^{\ 2} \sim \gamma^4 = \left(\mathrm{E}/mc^2\right)^4$).

The γ-rays flux after collimator is proportional to its solid angle, as well as additional energy spread (see Section 2.4). Therefore, the use of collimator with radius of $r = L\sigma_{\theta_x}$ could optimize flux and energy resolution.

It is important to note, that beam parameters can be accurately measures in storage rings. Therefore, exact γ-ray spectrum after collimator can be calculated for each FEL wavelength and storage ring energy. The knowledge of the spectrum and its tunability should allow deconvolution of the measurements and improve energy resolution in factor 5-10.

More straight forward improvement of the energy resolution is to increase β_x. We plan to arrange special collision point with β_x=40. Table III summarized expected performance of the Duke Compton γ-source and contribution of different factors to the energy resolution.

Table III. Performance of the Duke Compton γ-source.

Parameter	*OK-4 FEL*	*Spontaneous radiation*	*Comment*
γ–Energy, [MeV]	5-240	200-820	
Total flux of γ–rays [1/sec]	10^8-$2\cdot10^{11}$	~10^8	
Relative energy resolution			
β_x=4m	±0.3-1.2%	~0.5-2%	Depends on energy.
β_x=40m	±0.05-0.15%		New design

Contributions to the energy spread:

Source	Contribution	Duke @ 1 GeV	Comments
FEL bandwidth	$\frac{\Delta\omega}{\omega}$	<0.01%	small
Source size	$\left(\frac{\gamma\sigma}{L}\right)^2$	<0.05%	small
e-beam energy spread:	$\frac{2\Delta\gamma}{\gamma}$	~0.1%	important
e-beam angular spread:	$(\gamma\sigma_\theta)^2$		
with 4 m β-function		<±0.55%	significant
with 40 m β-function		<±0.06%	important
Target/Collimator size	$\left(\frac{\gamma r}{L}\right)^2$		depends on user

3.4 Status of the source.

The Duke storage ring is fully operational now in 0.25-1.1 GeV range. Injection occurs on 0.25-0.28 GeV and then energy is ramped. The OK-4 system is in the process of installation into south straight section of the ring. The start of the OK-4 operation is planed for January, 1996 with 6 eV photons. First γ-ray beams will be available immediately after the OK-4 is operational. There are no problems to generate γ-rays with 10 to 40 MeV - electrons will be kept inside the ring.

Higher energy γ-rays will cause electrons to die and they should be refilled. The Duke ring linac (operating now at 280 MeV) is capable of delivering ten times more electrons that will be lost. Its energy will be up-graded to 450 MeV in July, 1996. For full scale operation of the Duke Compton γ-source, the linac energy must be increased to 1-1.1 GeV for full energy injection. In addition, storage ring shielding should be up-graded to stand higher losses.

The OK-4 FEL has only linear polarization and will produce linearly polarized γ-rays. It is possible to replace its tunable elliptical wigglers such as designed for APS light source and to select desirable polarization of γ-rays.

Main background for the experiments with Duke Compton γ-source will be bremsstrahlung radiation. Direct measurement, performed by TUNL group, confirmed our expectation that background will be 4-6 orders of magnitude lower then γ-rays flux. It creates almost perfect conditions for nuclear physics experiments at our source. The TUNL group plans to start experiment in yearly 1996.

4. CONCLUSIONS

The Duke storage ring is now fully operational. The OK-4 FEL is in the process of installation in the south straight section of the Duke ring. The commissioning of the OK-4 magnetic system with electron beam is scheduled for September, 1995. The start of lasing experiments in the deep UV is planned for December, 1995, when new end-of-arc vacuum chambers and optical cavity will be installed.

5.ACKNOWLEDGMENTS

Authors would like to thank Guram Kezerashvilly (BINP, Novosibirsk) who attract our attention in 1991 to the fact that the Duke Storage Ring with 100 MeV energy acceptance is ideally suited for intermediate energy γ-ray facility. We also would like to thank Prof. Karl D. Straub (DFELL) who gave (in 1993) us copy of the paper on proposal of testing QED $\gamma\gamma \rightarrow e^+e^-$ and asked if we can do it.

We very thankful to all TUNL (Triangle University Nuclear Laboratory) group, in particular T.Scott Carman, Carol Y.Scarlet, Eric Shcreiber, N. Russel Roberson and H.W.Weller, for their enthusiasm, encouraging discussion and independent verifications of our predictions.

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6. REFERENCES

[1] "Commissioning of the Duke Storage Ring", V.Litvinenko et al., In Proc. of 1995 Particle Accelerator Conference, Dallas, Texas, May 1-5, 1995

[2] "Duke FELL Storage Ring Gamma Ray Facility", Vladimir N. Litvinenko, Internal Report, 29 July 1993, FELL, Duke University, Durham.

[3] "Production of Gamma-Rays for Nuclear Physics Using the Duke Free-Electron-laser Facility" T.Scott Carman, Carol Y.Scarlet, Eric Shcreiber, N. Russel Roberson and H.W.Weller, Technical Report, February *, 1995, Triangle University Nuclear Laboratory, Duke University, Durham

[4] Proceedings of the Triangle University Nuclear Laboratory Workshop on the Development of a Polarized Gamma-Ray Beam", December 16-17, 1994, Durham, NC;

[5] see for example:
L.Federici et al., Nuovo Cimento **59B** (1976) 461
A.M.Sandorfi et al., IEEE Trans.Nucl.Sci. 30 (1983) 3083
G.Kezerashvili, Proc. of 8th Seminar on EM interaction in Nuclei at Low and Medium Energies, Moscow, 2-5 December 1991, Moscow (1992) p.212

[6] "High peak Pulse Power Operation of the OK-4?Duke XUV FEL", V.Litvinenko, B.Burnham, J.M.J.Madey, Y.Wu, these Proceedings.

[7] "Duke storage ring FEL program", V.Litvinenko et al, SPIE Vol.1552 (1991) 2.
"UV-VUV FEL Program at Duke storage ring with OK-4 optical klystron", V.Litvinenko, J.M.J.Madey and N.A.Vinokurov , IEEE PAC 1993, v.2, p.1442
V.Litvinenko, B.Burnham, J.M.J.Madey, Y.Wu, Nucl. Instr. and Meth.,A358 (1995) 369-373
V.Litvinenko, Y.Wu, B.Burnham, J.M.J.Madey, Nucl. Instr. and Meth.,A358 (1995) 349

[8] L.D. Landau and E.M. Lifshitz, "The Classical Theory of Fields", 6th edition, Pergamon Press, 1994

[9] V.Berestetsky, E.Lifshitz, L.Pitaevsky, "Relativistic Quantum Theory", Nauka, 1968, Part I; (L.D. Landau and E.M. Lifshitz, the Course of Theoretical Physics, V.4, Pergamon Press)

Short-wavelength light sources at Duke storage ring.

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ABSTRACT

A 1.1 GeV electron storage ring is now fully operational at the Duke University Free Electron Laser Laboratory (DFELL) [1]. This ring is dedicated to drive a variety of very high brightness short-wavelength sources ranging from UV to gamma-rays.

In this paper we present overview of short-wavelength radiation sources including THE OK-4(XUV FEL, wiggler radiation and inverse Compton γ–rays), X-ray bend-magnets synchrotron radiation, soft X-ray NIST undulator radiation and hard X-ray inverse Compton source.

We also describe status of the sources and our short-term and long-term plans.

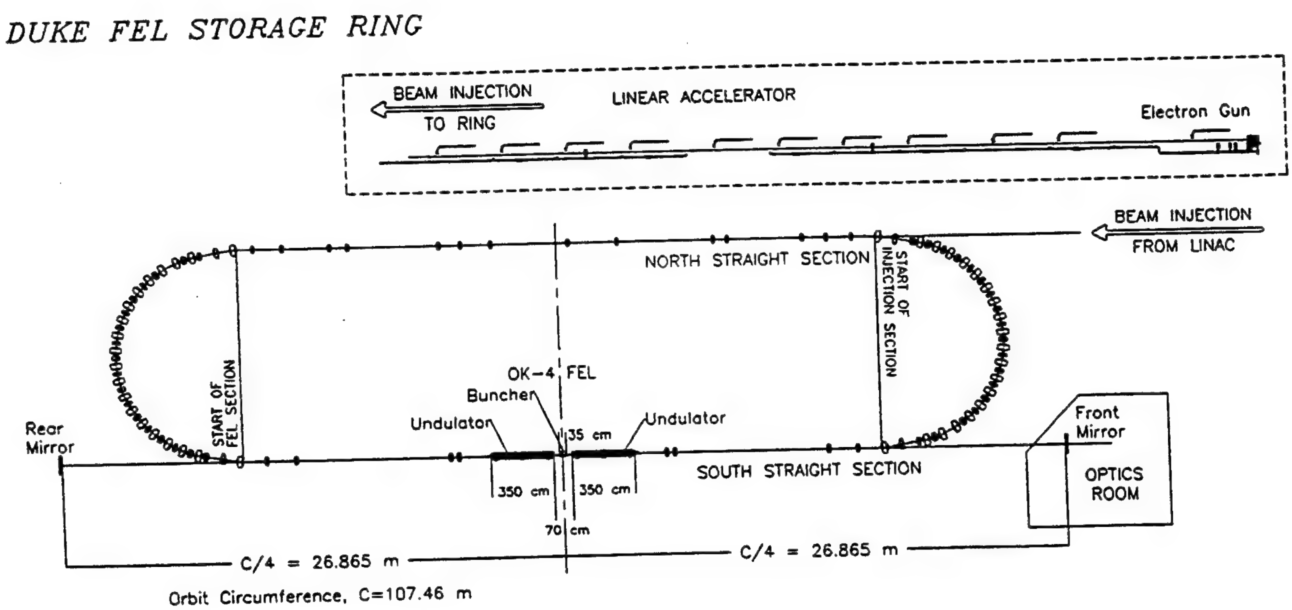


Figure 1. Layout of the Duke FEL storage ring and 280 MeV linac-injector. (North is up, West is to left).

I. INTRODUCTION

The third generation 1.1 GeV Duke storage ring is designed to drive UV and soft X-ray FELs as well as to produce high brightness synchrotron radiation from the bending magnets and insertion devices. The ring itself is a strong focusing race-track with two 34 meter long straight sections. The south straight section lattice is designed to optimize FEL operation with 7 to 28 m long FELs. The north straight section is used for injection and installation of the RF system and synchrotron radiation insertion devices: the NIST undulator and future hard-X-ray Inverse Compton source. There are plans for installation of a variety of FELs and undulators in the straight sections. Therefore, the ring lattice is flexible to be adjusted for variable configurations in straight section without reduction of the ring performance and its dynamic aperture.

0-8194-1881-1/95/$6.00

Spontaneous radiation from two bending magnets will be available at the end of 1995 after installation of permanent crotch-chambers. Then, the OK-4 FEL and the NIST undulator will be brought into operation.

The first FEL project, the UV-VUV OK-4 FEL, based on the collaboration of the Duke FEL Laboratory and Budker Institute for Nuclear Physics (BINP, Novosibirsk, Russia) is under way. The OK-4 FEL has arrived from Novosibirsk at the Duke FEL laboratory and is in the process of installation. The OK-4 FEL could be first of forth generation light sources in VUV range.

We used definition of short wavelength sources accepted by FEL community: wavelength is less then 1 micron. It left out of this paper an excellent source - MARKIII IR FEL operation in the Duke FEL laboratory since 1991. The MARKIII FEL is phase and frequency locked to all storage ring based light sources to be used for pump-probe experiments [2].

The phase-locking of different sources is unique feature of the Duke FEL facility.

II. THE DUKE STORAGE RING

The layout of the Duke storage ring and linac is shown in Figure 1. The ring itself is a strong focusing race-track with two 34 meter long straight sections. The south straight section lattice is designed to optimize FEL operation with 7 to 28 m long FELs. The north straight section is used for injection and installation of the RF system and synchrotron radiation insertion devices. The main parameters of the Duke storage ring are summarized in Table I. Detailed information on the Duke storage ring can be found in Ref. [1] and Ref. [6].

The commissioning of the 1 GeV Duke Storage Ring began in November, 1994 with the demonstration of injection, storage and ramping to 1 GeV at the first attempt. The ring is now operational with designed parameters. The Duke project is unique in that the storage ring and linac were designed, constructed and commissioned by a small new University laboratory.

The RF system of the Duke storage ring operates on 64-th harmonic of revolution frequency and can support maximum of 64 electron bunches. We are considering the use one bunch operation and multibunch operation (trains of 2-40 bunches with a gap to avoid ion capturing).

Table I. Parameters of Duke Storage Ring

Storage ring	Design	Measured/Achieved [1]	Comment
Ring circumference [m]	107.46	107.46±0.003	Central orbit
Operating energy [GeV]	0.25 - 1.0	0.2-1.1	With ramping
Injection energy [GeV]	0.25 - 1.1	0.2-0.28	0.5 (1996), 1.1 GeV (1997)
RF frequency - 64 th harmonic [MHz]	178.547	178.547±0.046	Tuning range
Energy acceptance, $\Delta E/E$, of ring	>±5.0%	±6 %	
Maximum β-functions [m], x and y	13.6, 21.3	12.92; 21.81	Without tuning*
Maximum η-function [m]	0.245		
Electron beam	**Design**	**Measured/Achieved**	**Comment**
Beam current, A	0.1 (1.0***)	0.115	In 5 bunches
Horizontal emittance, m*rad	$18 \cdot 10^{-9}$	$17\text{-}19 \cdot 10^{-9}$	At 1 GeV
Vertical emittance, m*rad	$1 \cdot 10^{-9}$	$<1 \cdot 10^{-9}$	
Bunch length, ps	33	< 70**	
Relative energy spread (low current)	0.0005		
at peak current of 130 A	0.0016		
Beam size in OK-4 [mm], σ_x and σ_y	0.27; 0.085		

* *these values are for theoretical settings; they are corrected to desirable values;*
** *limited by the instrument resolution; requires verification;* *** *final specification of the ring.*

The facility is comprised also the 280 MeV linac-injector (which will be up-graded in steps to 1 GeV) and linac-to-ring (LTR) channel with vertical chicane. All dipoles on the Duke storage ring, including those in the injection chicane, are fed by one power supply, while all quadrupoles have individual power supplies. This feature provides flexibility for the lattice design.

The 1 GeV Duke Storage Ring was very successfully commissioned with performance exceeding initial specifications [1]. We did not experience any problems tracking the beam through the LTR, the chicane, and the storage ring from the first shot without use of any correctors. There was no problem storing the beam and ramping the energy from 230 MeV to the design energy of 1 GeV. Later, the beam was ramped to 1.1 GeV as well. The commissioning of the Duke ring has resoundingly demonstrated the effectiveness of the lattice, control system and alignment. Stacking the electron beam with 100% efficiency using one kicker (instead of the designed three) was achieved.

III. SHORT WAVELENGTH FEL LIGHT SOURCES

Short wavelength FEL, spontaneous radiation and Inverse Compton radiation sources driven by the Duke electron storage ring are sketched on Fig.2. The storage ring provides 34 meter long straight section for high average and peak power UV/XUV FELs, the high brightness soft X-ray radiation from the NIST undulator and hard X-ray radiation from Inverse Compton source, six ports with broad band synchrotron radiation and 10 to 250 MeV Inverse Compton gamma-rays from the UV FEL.

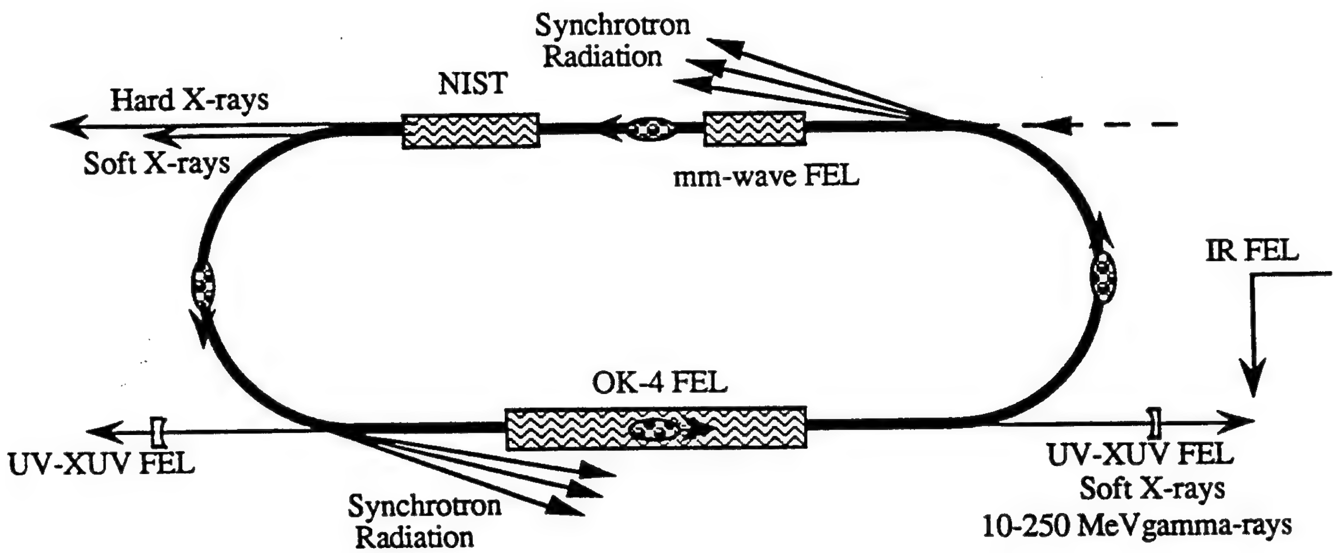


Fig. 2 Layout of the Duke ring short wavelength light sources.

The short wavelength light sources include:

South straight section: The THE OK-4sources:

- High peak and average-power coherent light in 60-400 nm region (FEL);
- Coherent harmonics in 4-100 nm region from the FEL system;
- High brightness wiggler radiation in 2-200 nm region from the OK-4 undulators;
- 5-250 MeV gamma-rays generated using Inverse Compton scattering;

North-East and South-West corners:

- White-light synchrotron radiation with a critical wavelength of 1.174 nm;

North straight section:

- Narrow-band spontaneous undulator radiation in 3.6-10 nm region from the NIST undulator;
- High brightness 1-10 keV X-rays generated using Inverse Compton scattering (ICXS).

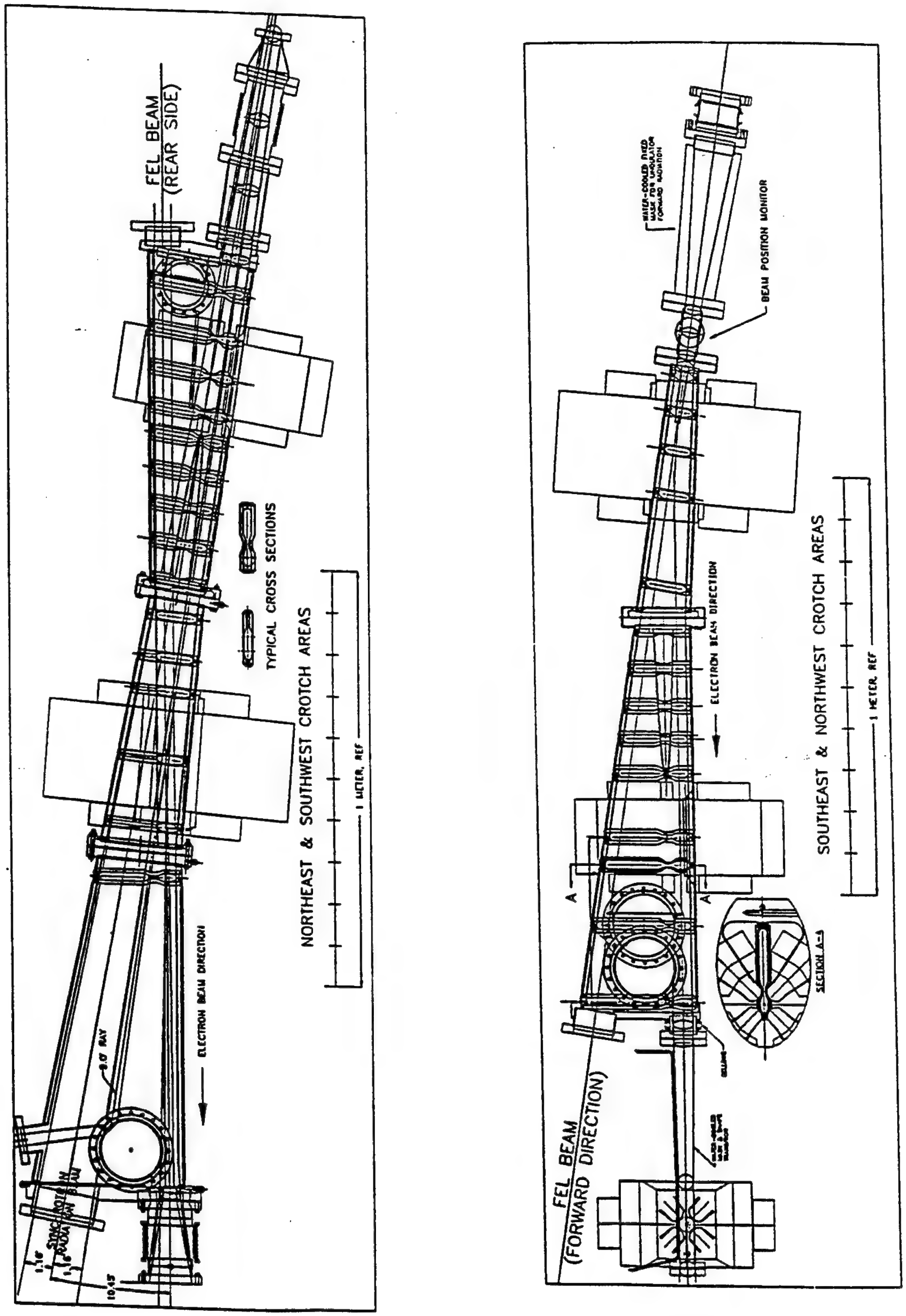


Fig. 3 Layout of the Northeast-Southwest and Southeast-Northwest crotch-chambers

We designed multipurpose end-of-the-arcs crotch chambers to serve all described light sources as well as to provide smooth low-impedance e-beam pass. Four of these chambers will be installed into corners of the storage ring. Two designs are used: a Northeast-Southwest crotch and a Southeast-Northwest crotch. Their designs are shown on Fig.3. These crotches will be installed in November-December, 1995. They are designed to support 1-2 A of the average beam current at 1 GeV.

The South-East crotche provides for front-leg of OK-4 optical cavity and extraction of UV-VUV-X-ray and γ-ray radiation. The same design of North-West crotche is used for extraction of the NIST soft-X-rays and the ICXS hard-X-rays.

The North-West and South-West crotches have different design to provide for extraction 2.32° of synchrotron radiation from 1.59 T bending magnets (@ 1 GeV) and back-leg of OK-4 FEL optical cavity.

IV. THE OK-4 XUV FEL

The OK-4 was the first operational UV FEL demonstrating lasing down to 240 nm. It still holds the short wavelength record for FELs. The OK-4 magnetic system and its projected performance are described in Refs. [7] and in Ref. [6] .

The tuning range of the fundamental harmonic wavelength of the OK-4 FEL is shown in Figure 4. The expected OK-4 average CW lasing power for 100mA and 1A average current are plotted in Fig. 5. The other parameters of the OK-4/DUKE UV-VUV FEL are presented in Table II.

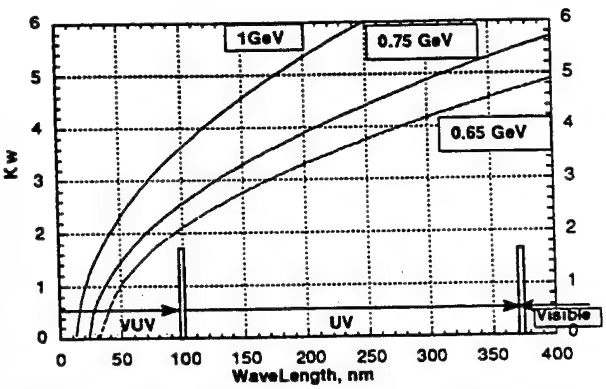


Figure 4. OK-4 tuning range at 0.65, 0.75 and 1 GeV.

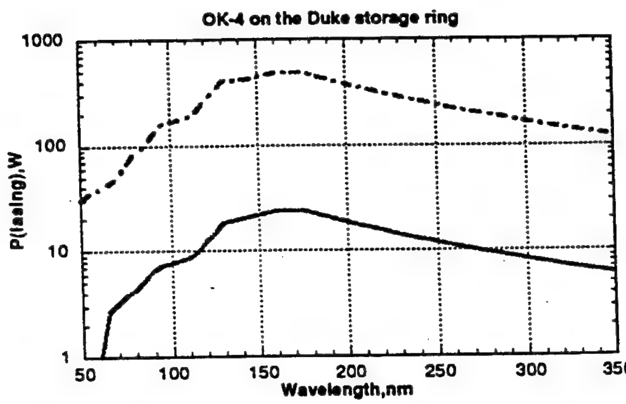


Figure 5. OK-4 FEL lasing power: solid line for 100 mA and dashed curve for 1 A average current.

Table II. Parameters OK-4/DUKE UV-VUV FEL

Tuning range, [nm]:	fundamental:	50-400	harmonics	4-100
Average Lasing Power, [W]	fundamental:	1-400	harmonics	0.001-1
Peak Lasing Power, [GW]	fundamental:	1-10	harmonics	0.001-0.1
Linewidth, [δλ/λ]	natural	$(1\text{-}3)\ 10^{-4}$	with linewidth narrowing	$(5\text{-}30)\ 10^{-7}$
Micropulse duration [psec]	natural	3-30	in super-pulse mode	0.1-2
Micropulse separation [nsec]	one bunch	358.45	64 bunches 5.60	
Spatial distribution			TEMoo	
Special features	Phase-locked with MARK-III IR FEL and other			

In a storage ring driven FEL only the average lasing power is limited. Thus, we can redistribute the lasing power using gain modulation to produce giant pulses with gigawatt levels of peak power and 50-100 Hz repetition rate. Fig.7 shows the optical peak power and full micropulse length in the Super Pulse mode [3] for the OK-4/Duke FEL operating at 200 nm. This mode of operation provides sufficient intracavity power to efficiently generate coherent harmonics of fundamental frequency. We plan to use additional wiggler, following the OK-4, tuned on harmonic of the OK-4 FEL to facilitate harmonics generation. These technique should allow us to generate soft X-ray down to the water window.

High average intracavity power of the OK-4 will be utilized for unique high power near-monochromatic γ-ray source. Detailed description can be found in Ref. [4]. Predicted performance of the γ-ray source is shown on Fig.7

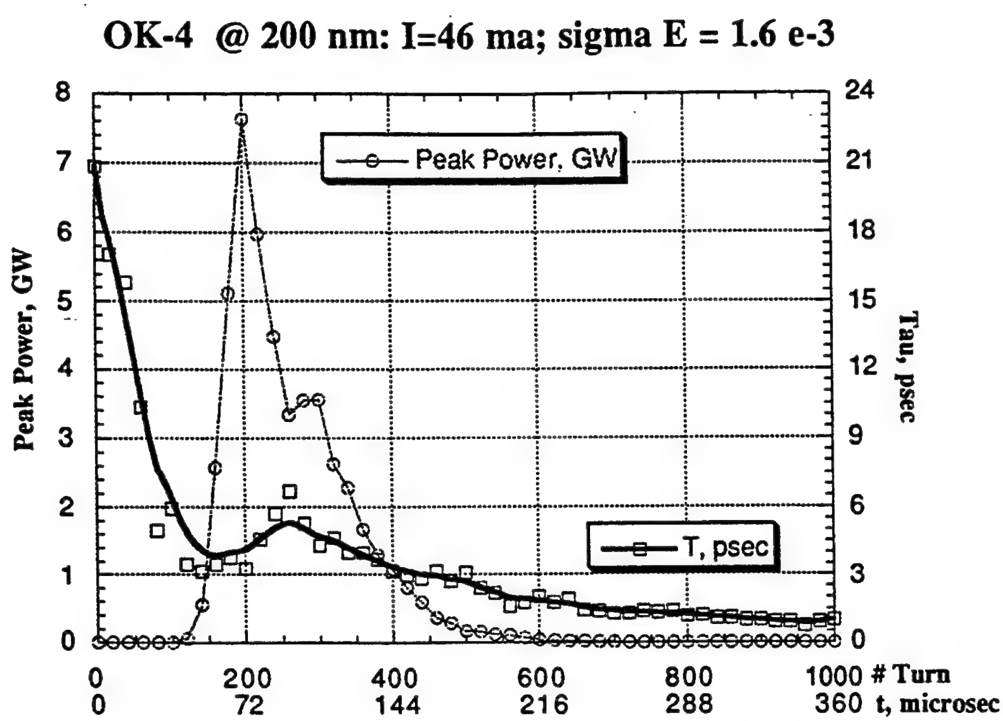


Figure 6. Typical OK-4 optical peak power and pulse duration in Super Pulse mode.

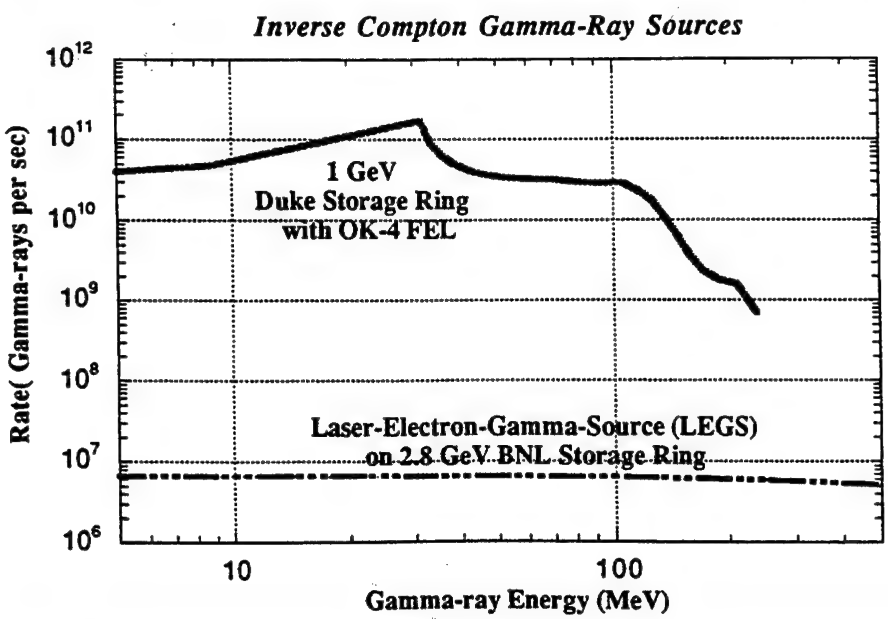


Fig. 7 Predicted rate for the OK-4/Duke ring γ-ray source compared with the LEGS facility [5].

Seven meters long OK-4 undulators produce 1 kW (with 1 A of average current) of soft X-ray spontaneous radiation with reach harmonic content. We plan to use this radiation for MFEL application program.

V. RADIATION FROM THE NIST UNDULATOR AND BENDING MAGNETS

The NIST undulator is located in north straight section and about 6 meters from north-west corner of the ring, where a port for it's radiation is placed. The electron beam lattice is optimized to maximize the brightness of this device. The electron beam size in this region measures of 0.19 mm (horizontal) and 0.018 mm (vertical). The tuning range and brightness of NIST undulator radiation at 1 GeV energy is shown in Fig.8. The NIST undulator brightness is competitive with the ALS undulators at LBL. The main parameters of the NIST undulator and a brief comparison with existing or planned US sources are given in Table III.

Table III. Parameters of NIST undulator

Period	[cm]	2.8
Peak Field (at gap of 10 mm)	[kGs]	5.4
Length	[m]	3.64

	NIST und. at Duke	*XIA (NSLS)*	*U5(ALS@LBL)*
Number of periods	130	35	89
Ring Energy [GeV]	0.5-1	1.5-3	1.5
Fundamental Wavelength range [nm]	3.6-21.6	1.2-18.8	3-24
Spectral Band Width (%FWHM)	1.3	18	1.2
TEMoo power (mW)@ 4nm	41	1.6	186

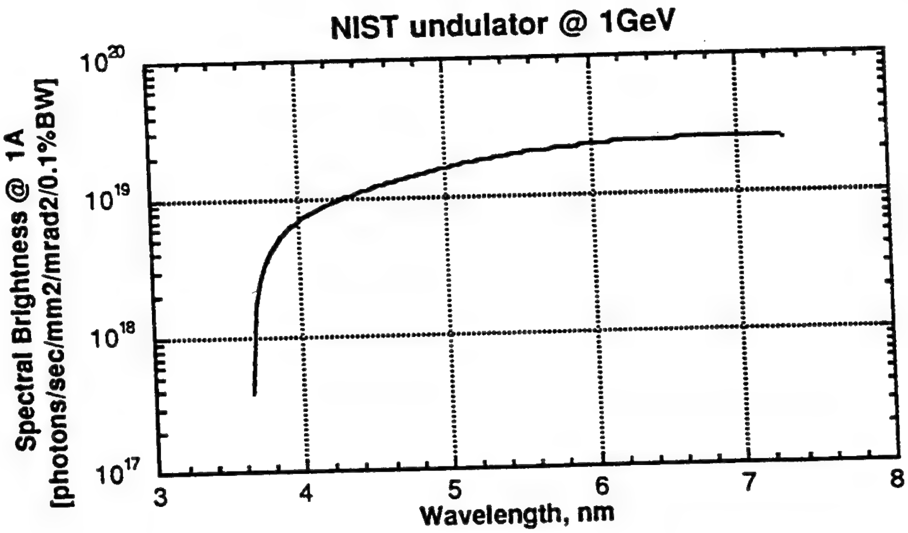


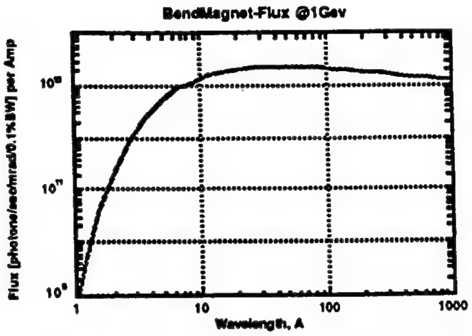
Fig. 8 The brightness of NIST undulator radiation at 1 GeV Duke storage ring.

In addition to the fundamental wavelength, the NIST undulator will produce third harmonic (1.2-7.2 nm range) and fifth harmonic (0.72-4.3 nm range) with comparable (with fundamental harmonics) spectral flux density. The maximum total power from NIST undulator at the Duke storage ring will approach 650 watts at 10 mm gap. Initially it will operate with 18 mm gap.

At present, the NIST undulator, transferred from NIST and installed on the Duke storage ring. However, it's magnetic performance does not meet design specifications. The magnetic measurements and shimming of the NIST undulator are in progress. At the end of 1995, the NIST undulator will be tuned to its specification and will be used for experiments.

Synchrotron radiation ports are located at northeast and southwest corners of the ring. Each of the multiport vacuum chambers will provide 240 watts of synchrotron radiation in a 2.3 degrees fan to be divided between 6-8 individual ports for different applications (difractometry, EXAFs, biological studies, lithography, etc.). The properties of the synchrotron radiation

are well known. Fig. 9 illustrates the quality of the Duke source.



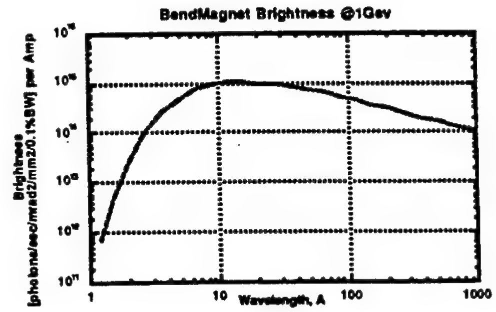


Fig.9 The spectral flux density (left) and spectral brightness (right) of bending magnet synchrotron radiation at 1 GeV with 1 A average current.

VI. HARD X-RAY INVERSE COMPTON SOURCE

Five-to seven meters of the Duke storage ring north straight section are allocated for novel very high brightness hard X-ray Inverse Compton Source (ICSX). Details of its principles and performance are published in Ref. [8]. The spectral brightness of this source is comparable with the-state-of-the-art third generation light source, as illustrated by Fig. 10.

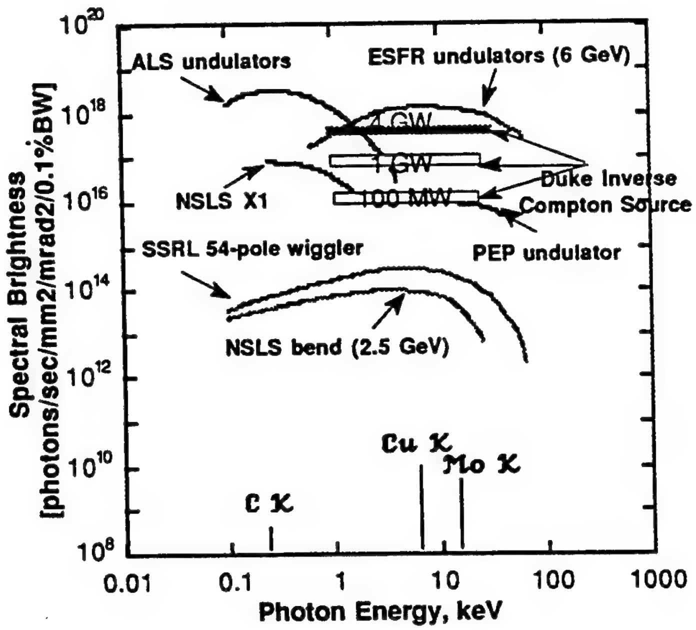


Fig. 10. Spectral brightness of the Duke Inverse Compton X-ray source with mm-wave peak power of 100 MW, 1 and 4 GW.

We propose use tightly focused mm-wave FEL [9] beam to pump these hard X-ray Inverse Compton source at the Duke storage ring. Our simulation show than we can create 30 kGs peak field in the waist of 1-3-mm FEL optical cavity and use it for generation of 6-20 keV X-rays. High EM field and small source size is more then make-up for modest energy of the Duke ring. Fig. 11 shows typical 30 kGs pulse in 3-mm Duke FEL.

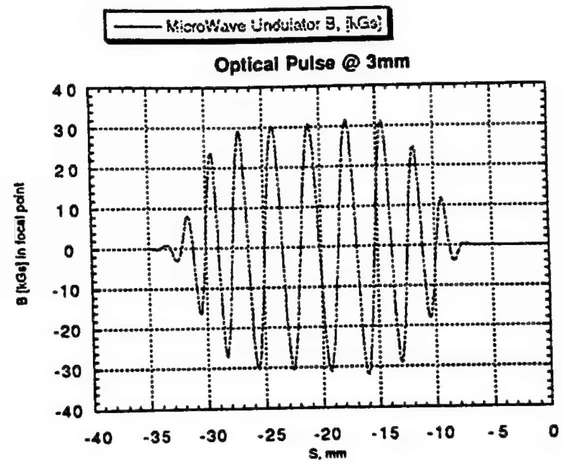


Fig.11 The 3 mm-wave pulse focused with 1.5 cm Rayleigh range for X-Ray production.

VII. DIAGNOSTICS.

The visible and the UV part of synchrotron radiation found its use for different pump-probe experiment [2] as well as for e-beam diagnostics The Duke storage ring has four end-of-arc ports for extraction of visible and UV portion of synchrotron radiation and the OK-4 optical system. These systems are in continuos development.

The optical diagnostics of the electron beam includes optics (mirrors, lenses, beam-splitters), TV cameras, screens, a dissector with 20 psec resolution, and a number of photomultipliers. Each corner is equipped with a small optical table to mount optical components. Soft-X-ray diagnostics will be developed in near future.

This Fall, the OK-4 visible and UV diagnostic system, arrived from Novosibirsk will be commissioned. It includes a variety of on-line spectrometers, 2-3 psec dissector, etc. The use of full diagnostic system would allow to measure and verify all important parameters of the electron and photon beams.

VIII. PLANS

We plan to install during next 12 months : 1) smooth end-of-arc crotch chambers, the OK-4 and the NIST front-ends; 2) electronics for the 60 existing strip-line BPMs with 1 micron resolution; 3) gun-kicker with 5 nsec bunch duration for single bucket filling; 4) two additional kickers to simplify injection.

Near term (before January, 1996) plans include installation and commissioning of the UV/VUV OK-4 FEL and the NIST undulator. Their radiation would be available in March, 1996. Synchrotron radiation from the banding magnets will be available in December, 1995.

Long term plans include upgrade of the linac to 400-500 MeV and later to 1 GeV, harmonics generation in the OK-4, up-grades of the OK-4 to 26 m, development of ICSX hard X-ray source, and more.

IX. CONCLUSIONS AND ACKNOWLEDGMENTS

The Duke storage ring is now fully operational. The OK-4 FEL is in the process of installation in the south straight section of the Duke ring. The commissioning of the OK-4 magnetic system, the NIST undulators with electron beam is scheduled for January, 1996. The start of user program with synchrotron radiation is planned for December 1995, when new end-of-arc vacuum chambers will be installed.

We acknowledge support from the Office of Naval Research under contract #N00014-94-C0818 and Air Force Office of Scientific Research under contract #F49620-93-1-0590

6. REFERENCES

[1] "Commissioning of the Duke Storage Ring", V.Litvinenko et al., In proc. of 1995 Particle Accelerator Conference, Dallas, Texas, May 1-5, 1995

[2] "Pico-second pump-probe using a FEL and synchrotron source", K.Straub, J.Madey, P.O'Shea, V.Litvinenko, E.Szarmes, G.Barnett, these Proceedings.
Internal Report, 29 July 1993, FELL, Duke University, Durham.

[3] "Physics of Super-pulses in storage ring FELs", V.Litvinenko, to be published.

[4] "High Power Inverse Compton γ-ray source at Duke storage ring", V.Litvinenko, J.M.J.Madey, SPIE vol. 2521, 1995 (to be published).

[5] A.M.Sandorfi et al., IEEE Trans.Nucl.Sci. 30 (1983) 3083

[6] "High peak Pulse Power Operation of the OK-4/Duke XUV FEL", V.Litvinenko, B.Burnham, J.M.J.Madey, Y.Wu, SPIE vol. 2521, 1995 (to be published).

[7] "Duke storage ring FEL program", V.Litvinenko et al, SPIE Vol.1552 (1991) 2.
"UV-VUV FEL Program at Duke storage ring with OK-4 optical klystron", V.Litvinenko, J.M.J.Madey and N.A.Vinokurov , IEEE PAC 1993, v.2, p.1442
V.Litvinenko, B.Burnham, J.M.J.Madey, Y.Wu, Nucl.Instr.and Meth.,A358 (1995) 369-373
V.Litvinenko, Y.Wu, B.Burnham, J.M.J.Madey, Nucl.Instr.and Meth.,A358 (1995) 349

[8] "Picosecond, tunable, high brightness hard X-ray inverse Compton source at Duke storage ring", V. N. Litvinenko, Y. Wu, B. Burnham, G. Barnett, J. M. J. Madey, SPIE vol. 2521, 1995 (to be published).

[9] V.Litvinenko, Y.Wu, B.Burnham, J.M.J.Madey, Nucl.Instr.and Meth., A358 (1995) 349

High Peak Pulse Power Operation of the OK-4/Duke XUV FEL

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ABSTRACT

A 1 GeV electron storage ring dedicated for UV-VUV FEL operation was commissioned last year at the Duke University Free Electron Laser Laboratory [1]. The XUV FEL project, based on the collaboration of the Duke FEL Laboratory and Budker Institute for Nuclear Physics (Novosibirsk, Russia) is described. The OK-4 UV FEL has arrived from Novosibirsk at the Duke FEL laboratory and is in the process of installation.

The main parameters of the DFELL storage ring, the OK-4 optical klystron, and the experimental set-up are presented. The parameters of the UV-VUV FEL are given and the possible future upgrades to this system are discussed. We have studied the dynamics of giant pulse generation in the Duke/OK-4 UV FEL.

We have developed a new macro-particle code for giant pulse simulation including all known mechanisms of storage ring FEL interaction. Results of these giant pulse simulations are presented in the paper.

A new mechanism of "super- pulse" generation was discovered during these studies. It allows the generation of peak power up to 10 Gigawatts using "phase-space" refreshment of the electron beam caused by synchrotron motion [2].

DUKE FEL STORAGE RING

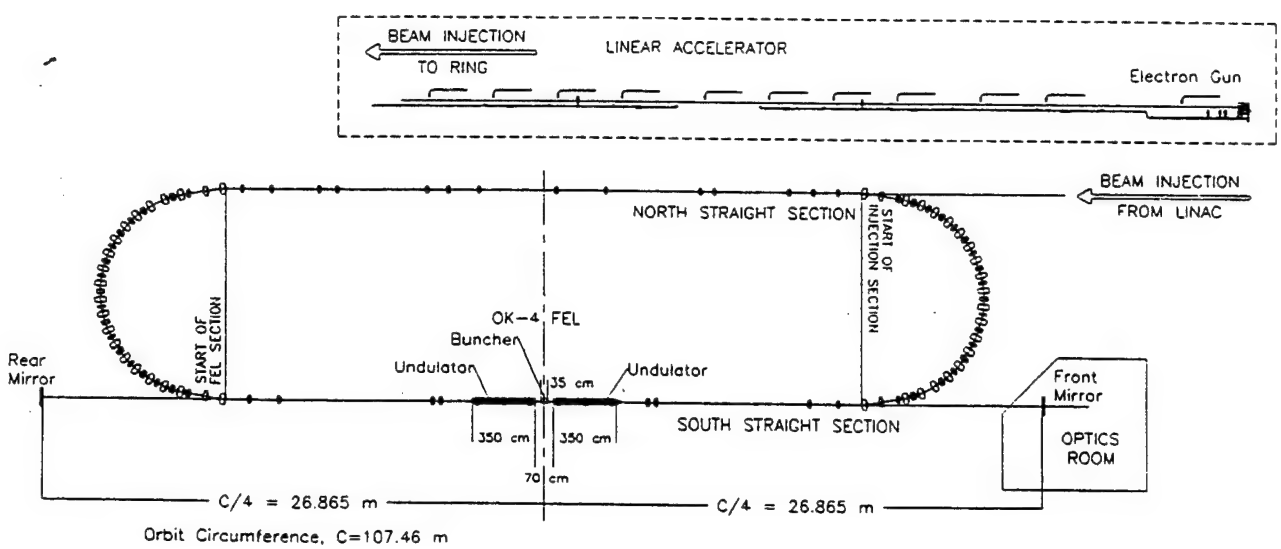

Figure 1. Layout of the Duke/OK-4 XUV storage ring FEL.

1. INTRODUCTION

In April 1992, Duke University Free Electron Laser Laboratory and Budker Institute of Nuclear Physics signed a Memorandum of Understanding on collaborative efforts in FEL research. As the first step in this collaboration, the OK-4 optical klystron system, including the magnetic system, vacuum system, optical cavity system and diagnostic system has been transferred to Duke FELL for XUV FEL experiments on the Duke storage ring. The layout of the Duke/OK-4 UV-VUV FEL is shown in Figure 1.

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1.1 The Duke storage ring

The Duke FEL electron storage ring is designed to drive UV and soft X-ray FELs. One of the two 34-meter straight sections is dedicated for FEL installation. The other straight section is used for injection, installation of the RF cavity, diagnostic systems, and NIST undulator (soft X-ray source). The main parameters of the Duke storage ring are summarized in Table I.

Table I. Parameters of Duke Storage Ring

Storage ring	Design	Measured/Achieved [1]	Comment
Operating energy [GeV]	0.25 - 1.0	0.2-1.1	With ramping
Injection energy [GeV]	0.25 - 1.0	0.2-0.28	
Ring circumference [m]	107.46	107.46±0.003	Central orbit
Arc and straight section length [m]	19.52; 34.21		
Revolution frequency [MHz]	2.7898	2.7898±0.0014	Tuning range
RF frequency [MHz]	178.547	178.547±0.046	Tuning range
Number of dipoles and quadrupoles	40; 64		
Betatron tunes, Qx and Qy	9.111, 4.180	9.118 4.145	Without tuning*
Orbit compaction factor, α	0.0086		
Natural chromaticities, Cx and Cy	-10.0, -9.78	-10, -9.8	
Compensated values, Cx and Cy	+0.1; +0.1	+0.1; +0.1	
Acceptances [mm mrad], Ax and Ay	56.0, 16.0	>43.0, >8.0	Limited by orbit*
		>54, >15.0	With corrections
Closed orbit (no correction) x and y, mm		<±5, <±4	Without tuning*
Energy acceptance, $\Delta E/E$, of ring	>±5.0%	±6 %	
limited by existing RF	±2.8%	±2.6%	At 1 GeV
Maximum β-functions [m], x and y	13.6, 21.3	12.92; 21.81	Without tuning*
β-functions around the ring		deviations <±20%	Without tuning*
Maximum η-function [m]	0.245		

Electron beam	Design	Measured/Achieved	Comment
Beam current, A	0.1 (1.0***)	0.115	In 5 bunches
Peak current, A	80-130 (350***)	> 50**	
Horizontal emittance, m*rad	$18\cdot10^{-9}$	$17\text{-}19\cdot10^{-9}$	At 1 GeV
Vertical emittance, m*rad	$1\cdot10^{-9}$	$<1\cdot10^{-9}$	
Bunch length, ps	33	< 70**	
Relative energy spread (low current)	0.0005		
at peak current of 130 A	0.0016		
Beam size in OK-4 [mm], σx and σy	0.27; 0.085		

* *these values are for theoretical settings; they are corrected to desirable values;*
** *was limited by the instrument resolution; requires verification;*
*** *final specification of the ring.*

1.2. The OK-4 optical klystron.

The OK-4 was the first operational UV FEL demonstrating lasing down to 240 nm. It still holds the short wavelength record for FELs. The OK-4 magnetic system is comprised of two 3.5 meter electromagnetic undulators and a buncher (3-pole compensated wiggler) located between them. The use of a buncher distinguishes optical klystrons from conventional FELs and permits the optimization of longitudinal dispersion for higher gain.

The OK-4 magnetic system has very high performance. The direct magnetic measurements and experimental results achieved with the OK-4 in Novosibirsk [3] have shown the practically perfect performance of this system. The main parameters of the OK-4 magnetic system are listed in Table II.

Table II. Main Parameters of OK-4 magnetic system

Undulator		**Buncher**	
Length [m]	3.40	Length [m]	0.34
Peak magnetic field [kGs]	(0.0-5.8)	Magnetic field [kGs]	(0-12)
Period [m]	0.10		
Undulator parameter, K	(0.0-5.42)	**OK-4 Magnetic System**	
Tuning range (λmax/λmin)	15.67	Total length [m]	7.8

1.3. Projected performance of DUKE/OK-4 XUV FEL

The tuning range (K vs wavelength) of the fundamental harmonic wavelength of the OK-4 FEL is shown in Figure 2. The parameters of the electron beam are very critical for performance of a short wavelength FEL.

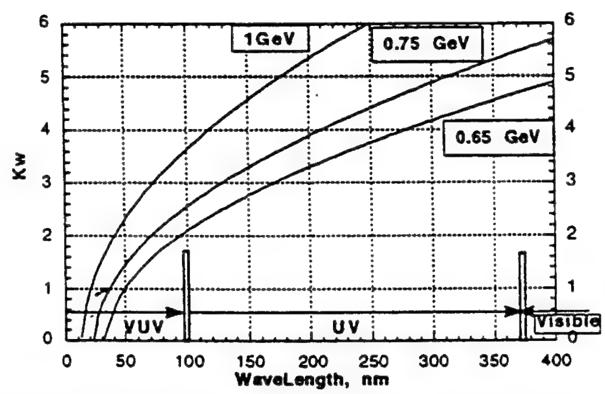

Figure 2. OK-4 tuning range at 0.65, 0.75 and 1 GeV.

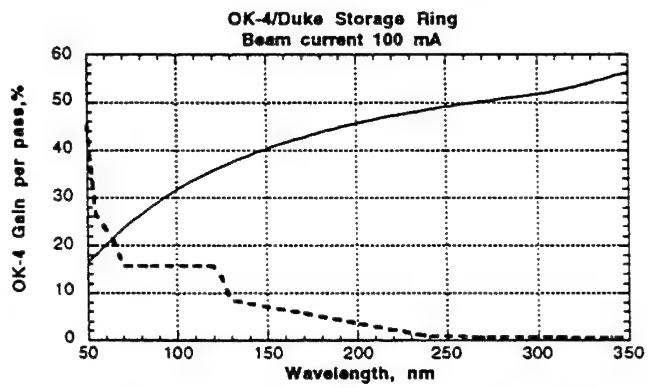

Figure 3. OK-4 gain vs. wavelength - solid curve. Dashed curve - lasing threshold gain (adopted from [4]).

At 1 GeV energy, the beam emittance is practically natural. Intrabeam scattering will affect only the electron beam lifetime (down to 30-45 minutes with 350 A peak current). Maximum achievable peak current will be limited by the impedance of the vacuum chambers, which have RF-smooth connections and transitions.

The 3-D OK-4 gain curve at a modest average current of 100 mA in the Duke ring is shown in Figure 3. Finite electron beam emittance and energy spread are taken into account. The finite emittance is responsible for gain drop in the short wavelength range.

In the VUV range average lasing power will be limited by gain degradation due to electron beam heating (even with the multifacet mirrors [5] we intend to use in this range).

The CW output of short wavelength storage ring FELs is limited by the energy spread growth of the electron beam due to its interaction with the FEL optical field [6]. Nevertheless, this power can be redistributed in time using a Q-switch technique [7] or gain modulation technique [3] to generate giant pulses with GW levels of power. Previous projections for the average and peak power performance of the OK-4 FEL have been published in [8].

The expected OK-4 average CW lasing power for 100mA and 1A average current are plotted in Figure.4. The high energy acceptance of the ring is very essential, because under these conditions the energy spread (excited by lasing) can reach 1%. The energy acceptance of ± 5% will provide an acceptable lifetime. These conditions can occur in the UV range where low loss mirrors are available. The other parameters of the OK-4/DUKE UV-VUV FEL are presented in Table III.

Table III. Parameters OK-4/DUKE UV-VUV FEL

Tuning range, [nm]	
fundamental:	50-400
harmonics	4-100
Linewidth, [$\delta\lambda/\lambda$]	
natural	(1-3) 10^{-4}
with linewidth narrowing [9]	(5-30) 10^{-7}
Micropulse duration [psec]	
natural	3-30
in super-pulse mode	0.1-2
Micropulse separation [nsec]	
maximal (one bunch)	358.45
minimal (64 bunches)	5.60
Spatial distribution	TEMoo

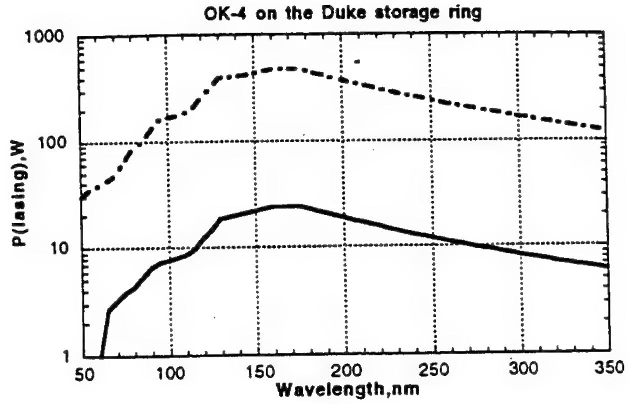

Figure 4. OK-4 FEL lasing power: solid line for 100 mA and dashed curve for 1 A average current.

We also expect 1-1.5 GW peak power in giant pulse mode. To test our expectations we have developed a computer program which includes all known phenomena affecting storage ring FEL performance. *During the study we discovered a new phenomenon- Super Pulses with ten to thirty times higher peak power than Giant pulses.*

The theory of storage ring FEL operation implemented in this program is published in [10]. In this paper we present a description of the code and summary of results for the OK-4/Duke UV/VUV FEL achieved using this code.

2. COMPUTER MODEL

We have developed a set of computer programs which include all known phenomena influencing operation of short-wavelength storage ring FELs (SRFEL). The high efficiency algorithms used in the code allow us to track up to thirty thousand macro-particles for tens of thousands of turns to simulate real-time self-consistent SRFEL operation. A detailed description of the code is published elsewhere [11].

The model we use here simulates an optical klystron with total length 2L comprised of two planar undulators (each with N_u periods of λ_u and undulator parameter of K_u) and a buncher occupying a length from $-z_i$ to z_i. [10]. The strength of the buncher can be adjusted to optimize FEL operation. With the buncher turned off the system becomes a conventional FEL.

2.1 Macro-particles

A macro-particle is described by its energy $\varepsilon = (E-Eo)/Eo$ and longitudinal position $s = ct_o$, where t_o is the electron arrival time at $z = 0$. It represents a cluster of electrons localized in (ε,s) phase-space and having standard distribution in transverse phase space. As was shown in [10], radiation of the macro-particle can be found analytically. This analytical capability makes these simulations possible. The maximum number of macro-particles in the program is 30,000.

2.2 Optical Wavepacket

We represent the FEL optical field, E, by a TEMoo mode with slowly varying complex amplitude $A_o(s)$,

$$\vec{E}_o(t,\vec{r}) = \mathrm{Re}\left\{\hat{e}_x A_o(s)\frac{\beta_o}{\beta_o - \mathrm{i}z}\cdot\exp\left[iks - \frac{k}{2}\frac{x^2+y^2}{\beta_o - \mathrm{i}z}\right]\right\}; \tag{1}$$

where $s = ct - z$ and c is the speed of light. The Rayleigh length is β_o with waist at azimuth $z=0$; x and y are transverse

coordinates, and $k=2\pi/\lambda$ is the optical wave vector. An optical wave packet is represented by an array (with maximum length of 30,000) of complex wave amplitude A[i] . The length of one array bin is equal to the total slippage in the FEL $\Sigma_t = \Sigma(L) - \Sigma(-L)$ (see Eq.(3)). This choice limits wavelength bandwidth to $\Delta k \sim 1/\Sigma_t$. This bandwidth is sufficient to include full width of the FEL gain profile. The program includes the energy detuning parameter which is set to the maximum gain.

2.3 FEL Parameters.

We use two complex arrays to represent individual macroparticle induced radiation. It is well known that the induced radiation (both real and imaginary parts) is shifted with respect to the optical wavepacket. This effect is essential for optical pulse evolution because it influences the super-mode structure [12]. This shift depends on electron energy. To properly model slippage of induced radiation, we used (in addition to the average value of real and imaginary parts of the gain) the first moments of the real and imaginary parts of the gain :

$$G_m = \int_{\Sigma(-L)}^{\Sigma(L)} s A_{ind}(s)\,ds \tag{2}$$

$$A_{ind}(s_o + \Sigma(z)) = -i\frac{k}{E_o\beta_o}\left(\frac{eK_uJJ}{2\gamma}\right)^2\left(\frac{d\Sigma}{dz}\right)^{-1}\int_{-L}^{z} dz_1 A_o(s_o + \Sigma(z_1))(\Sigma(z) - \Sigma(z_1))FF(z,z_1)e^{i\{k_u(z-z_1)-k(\Sigma(z)-\Sigma(z_1))\}}$$

where $\Sigma(z)$ is the FEL slippage function:

$$\Sigma(z) = z\frac{1+K^2/2}{2\gamma^2}\begin{Bmatrix}-\\+\end{Bmatrix}\frac{\Delta s_B}{2}\left(\frac{\gamma_o}{\gamma}\right)^2\begin{Bmatrix}z<-z_i\\ z>z_i\end{Bmatrix} \tag{3}$$

and Δs_B is the slippage in the buncher. The function $FF(z_1,z_2)$ is a complex function derived analytically which takes into account the influence of both horizontal and vertical e-beam emittances and the TEMoo mode structure [10,13].

The spontaneous radiation is represented by an array with exact values of radiation amplitude into one bin which is multiplied by the square root of the number of electrons in the macro-particle. We use the exact analytical expressions for spontaneous radiation into the TEMoo mode, including energy dependence and e-beam emittance [10]:

$$|A_{sp}|^2 = \frac{2k}{\beta_o}\left(\frac{eK_uJJ}{\gamma_o}\right)^2\int_{-L}^{L}\int_{-L}^{L} dz_1 dz_2 FF(z_1,z_2)e^{i[k(\Sigma(z_1)-\Sigma(z_2))-k_u(z_1-z_2)]}, \tag{4}$$

where $k_u=2\pi/\lambda_\upsilon$. Before adding this expression to the wavepacket, the amplitude of the spontaneous radiation is multiplied by a random number with unit RMS value and complex exponent with random phase.

A very similar algorithm is used for the random energy kick caused by the FEL interaction. This energy kick is represented by an array of exact RMS kick values. The amplitude of the kick depends on the amplitude of the local optical field (see [10]) and is random in phase:

$$\langle \Delta E^2 \rangle = \frac{1}{2}\left(\frac{eK_uJJ}{2\gamma_o}\right)^2|A_o|^2\int_{-L}^{L}\int_{-L}^{L} dz_1 dz_2 FF(z_1,z_2)e^{i[k(\Sigma(z_1)-\Sigma(z_2))-k_u(z_1-z_2)]} \tag{5}$$

Each of the arrays described above contains 10,001 values for a 4% energy deviation range with a step of $\delta\gamma/\gamma=4\cdot10^{-6}$. In order to optimize the FEL performance we provide the capability to interactively change the slippage in the buncher and energy detuning. For a chosen FEL geometry, wavelength, and central electron energy, a special program tabulates one real and eight complex double integrals [13] required for the four arrays described above as functions of electron energy, with an energy step of $4\cdot10^{-6}$. These integral data are saved in a file. These integral calculations take about one hour of CPU time on a SPARC workstation. The main program reads this file and in a few seconds produces all of the necessary arrays for the

chosen slippage of the buncher, and recommends the optimum energy detuning parameter.

The main program is composed of four main subroutines:

FelCoefficients - Reads tabulated integrals and calculates arrays of real and imaginary values of macro-particle gain and moments. It also recommends the optimum value of energy detuning.

RingPass - Includes the exact algorithm of a round trip pass of the macro-particle around the storage ring, i.e. RF cavity, momentum compaction factor (variation of s), synchrotron radiation damping, and quantum jumps of the energy. The exact implementation of the algorithm is described in [9].

FelInteraction - The main part of the code. This subroutine finds the two wavepacket bins the particle is interacting with and calculates the wavepacket optical field using a linear (small signal) approximation. It also calculates the energy bin corresponding to the instantaneous value of the macro-particle energy (including energy detuning). Next it adds the spontaneous radiation (from the proper energy bin) into the wavepacket bins proportional to their overlap (see Fig.5). The induced radiation is calculated (from the proper energy bin ε_bin) using the complex gain g_{av}, its first moment g_{mom}, and optical wave amplitude A_o:

$$\begin{aligned} A_o &= A[i]\cdot(1-X) + A[i+1]\cdot X \\ A[i] &= A[i] + A_o\cdot(1-X)\cdot\{g_{av}[e\_bin] - g_{mom}[e\_bin]\cdot X\} \\ A[i+1] &= A[i+1] + A_o\cdot X\cdot\{g_{av}[e\_bin] + g_{mom}[e\_bin]\cdot(1-X)\} \end{aligned} \tag{8}$$

where X is the overlap of macro-particle radiation and wave-packet bins (see Fig.5).

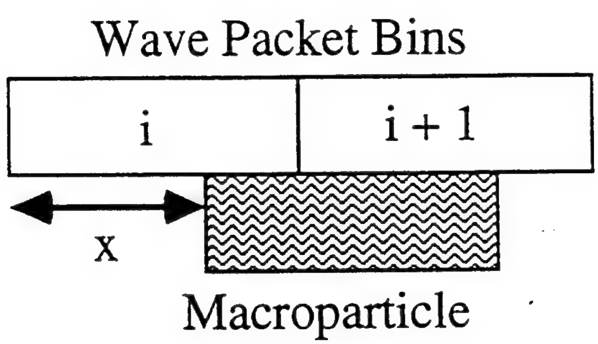

Figure 5. Optical wave and electron bin overlap

Finally, the program varies the electron energy using the energy kick array, optical wave amplitude, and random phase.

CavityPass - implements exact transformation as described by:

$$A_{n+1}(s) = \sqrt{R}\cdot A_n(s-d) \tag{9}$$

where R is the round trip reflectivity and d is the detuning of the optical cavity. It accumulates the total value of the detuning from pass to pass and moves the wavepacket array only for the integer part of the accumulated detuning. It passes the non-integer part into the FelInteraction subroutine where it is taken into account in the bin search and interaction. The algorithm is described in [14].

Table IV. Typical contain of input file *"input.uv"*

Num_Part	Num_Rev	Num_Damp	Mod_Num	Num_Wave_Packet		
10000	10000	11000	100	10000		
Reflectivity per Mirror	Cavity_Detune [bins]					
0.98E0	0.00E0					
Energy Ring [GeV]	Circumference [cm]	Num_Harm_RF	Volt_RF [GV]	α_Comp		
1.0	107.46E2	64	8.0E-4	8.601566E-3		
σE/E	FEL λ [cm]	Energy_detune/E	# Und Per.	$\Delta S_B/\lambda$	Und. Per.[cm]	# of e-
1.5900E-3	2.0E-5	0.002364	33.5	10.00	10.0	1.0E+11
Emittance x [cm*rad]	Emittance y [cm*rad]	z_i [cm]	βx [cm]	βy [cm]	βo[cm]	
18.0E-7	18.0E-9	30.0	350.0	350.0	185.	

Additional subroutines provide file service and interactive mode of operation. A typical input file for the code is listed in Table IV. The underlined parameters are used by the program to tabulate integrals. Other parameters in the code can be changed interactively without the one hour delay for tabulation of integrals. While interaction operation complicates the tabulation program (9 integrals instead of three), it gives the very important advantage of flexibility and speed.

3. RESULTS OF GIANT PULSE SIMULATIONS.

Using the codes described above, we have studied laser pulse and e-beam dynamics of the OK-4/Duke UV FEL in Giant pulse mode in the deep UV and VUV range. We assume an e-beam current of 10 to 100 mA average current (typical value 46 mA) and 10-100 A peak current.

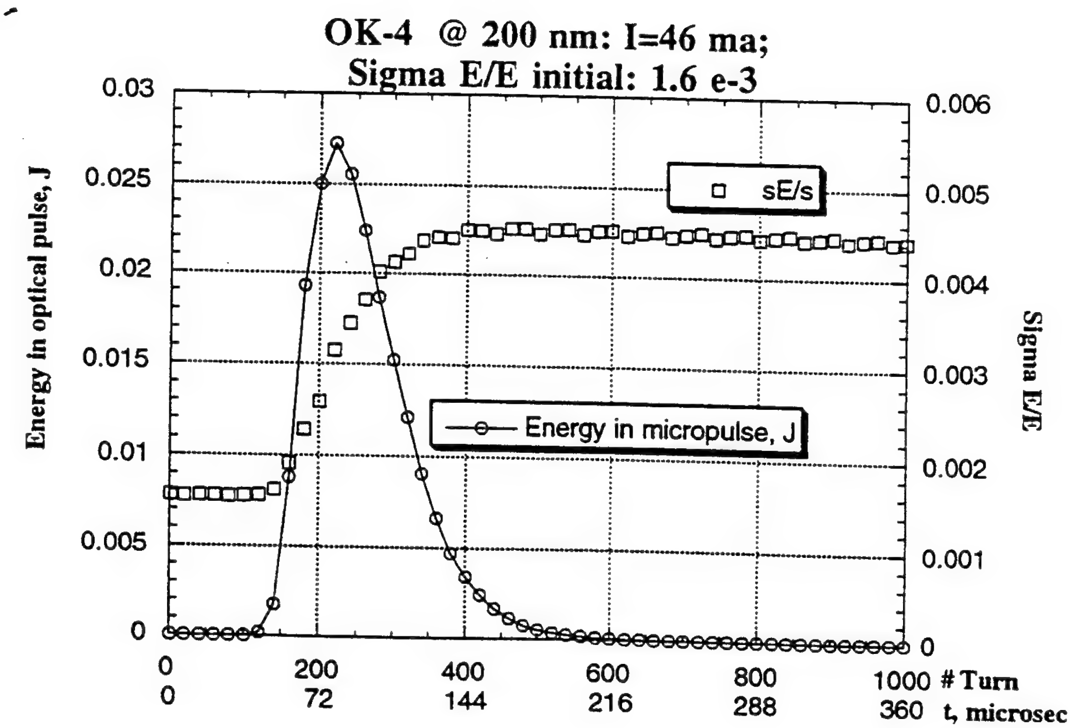

Figure 6. Typical OK-4 FEL optical micropulse energy and e-beam energy spread evolution during Giant Pulse.

Giant pulse mode in the OK-4/Duke FEL will be realized using gain modulation. The electron beam will be displaced by a special deflector from the axis of the optical cavity to reduce FEL gain below cavity losses. The cooled beam, with energy spread defined by microwave bunch-lengthening, will return back to the axis during 25 to 50 e-beam revolutions to ensure adiabatic transition of the closed orbit and absence of residual betatron oscillations. Thus, the FEL will start from noise and the laser power will grow exponentially until it starts to heat the beam. As the energy spread grows, the FEL gain decreases. Maximum power will be reached when FEL net gain is zero. The heated e-beam will be deflected from the axis for 2-4 damping times (15 to 30 msec for 1 GeV operation) to be cooled. The giant pulse may then be repeated.

A typical Giant pulse shape for the OK-4/Duke FEL operating at 46 mA (10^{11} electrons) at 200 nm is shown in Fig.6. Fig.7 shows the optical peak power and full micropulse length for the same beam parameters in the Super Pulse regime [15]. Optical cavity detuning is -3.1 microns for these runs.

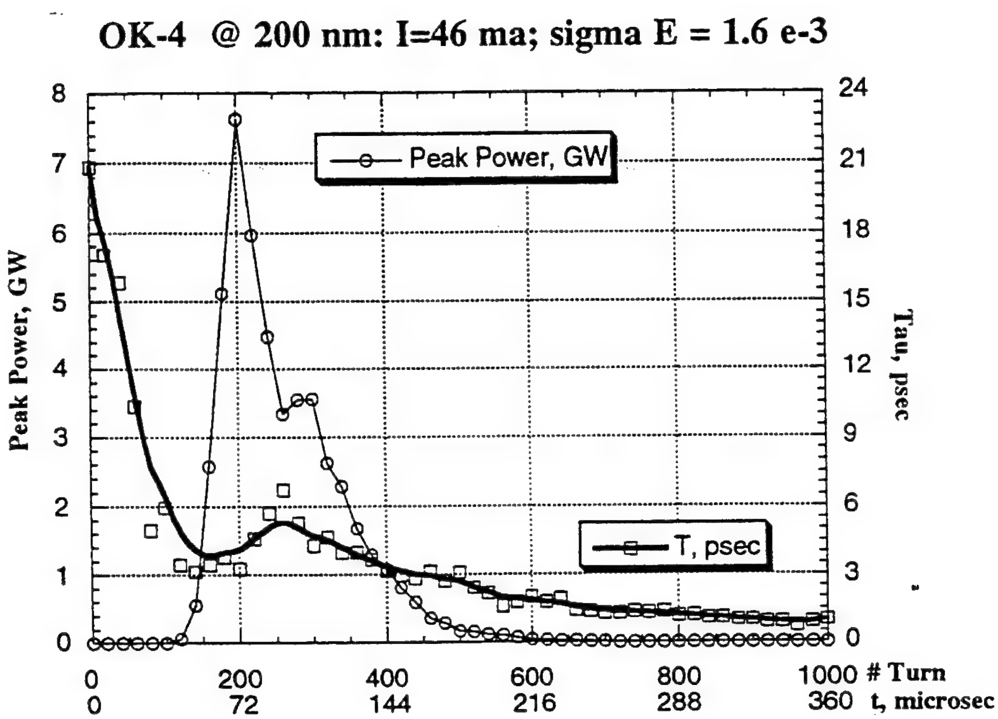

Figure 7. Typical OK-4 optical peak power and pulse duration in Super Pulse mode.

While the energy in the micropulse in these simulations corresponds to earlier theoretical predictions [8], the peak power is 10 times higher than expected. This fascinating discrepancy is caused by the "Super Pulse" phenomena [15] and can be exploited for production of very short pulses with exceptionally high peak power.

Typical Poincare plots for Super Pulse mode of operation are shown in Fig.8. The "cold" beam is returned back to the FEL axis at turn #1 (Fig. 8a). It has natural distribution in phase space with $\sigma_E/E = 0.16\%$ and $\sigma_s = 2.73$ cm. The OK-4 FEL starts up from spontaneous radiation noise and the 200 nm optical power starts to grow increasing 10 fold every 20 turns. After 100 turns, the optical power grows to the level when it begins to affect the energy spread of the electron beam. Fig. 9 shows a typical profile of the energy diffusion coefficient as a function of electron energy and location. Diffusion is highly peaked near the center of the electron bunch and negative energy deviations. The diffusion dependence together with synchrotron oscillations create specific conditions for Super-pulse generation. A qualitative description of the processes involved are presented in Fig. 10 and Fig. 11. It is essential that after crossing the "hot phase-space spot", the electron energy spread growth be a factor of 2-3 higher (see Figs. 8c,d,e) and their gain become very small. Thus, this process can become maximum for one period of synchrotron oscillations, which is 120 turns for the Duke/OK-4 system. Then the electron beam energy spread grows up everywhere (see Fig. 8.f), and the electron beam should be cooled.

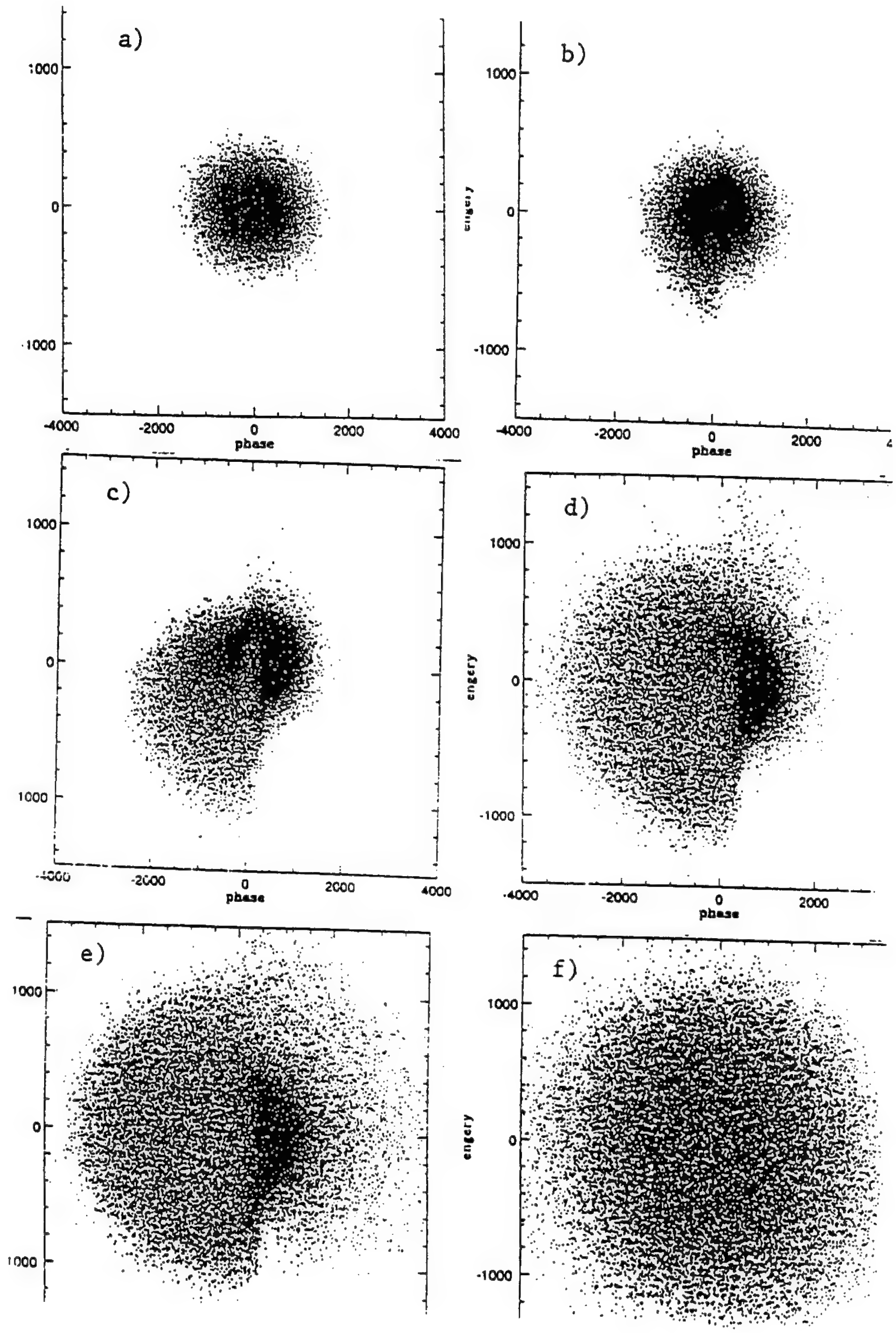

Figure 8. Poincare (E,s) phase-space plots for Super Pulse mode of the OK-4 FEL:
Relative energy deviation ($\delta E/E_o$) is in steps ($4 \cdot 10^{-6}$ per step); longitudinal position is in bins ($1.555 \cdot 10^{-3}$ cm per bin);
Full vertical scale is $\delta E/E_o$ $\pm 0.6\%$; full horizontal scale is ± 6.22 cm (± 207 psec).

a) Turn #1: cold beam $\sigma_E/E=0.16\%$;
b) after 100 turns (Ppeak=4 MW);
c) after 130 turns (Ppeak=200 MW);
d) after 170 turns (Ppeak=3.5 GW);
e) 210 turns : at peak (7 GW);
f) after 400 turns: hot beam with $\sigma E/E=0.44\%$.

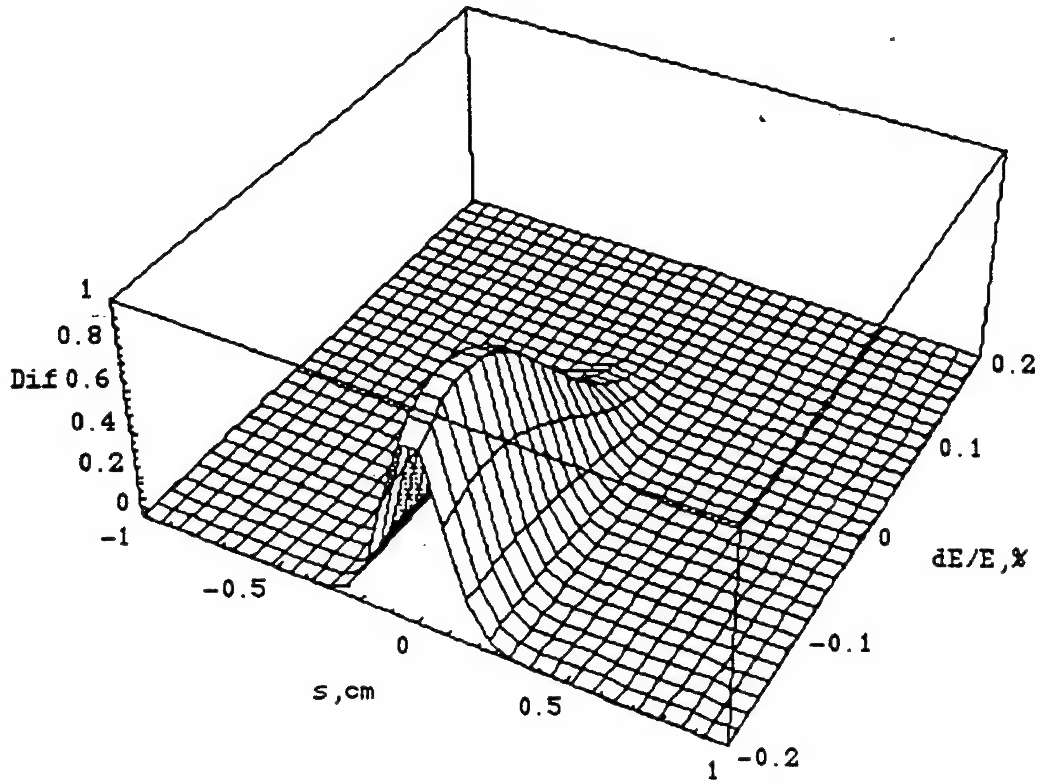

Figure 9. Typical dependence of electron energy diffusion coefficient for OK-4 operation at 200 nm.

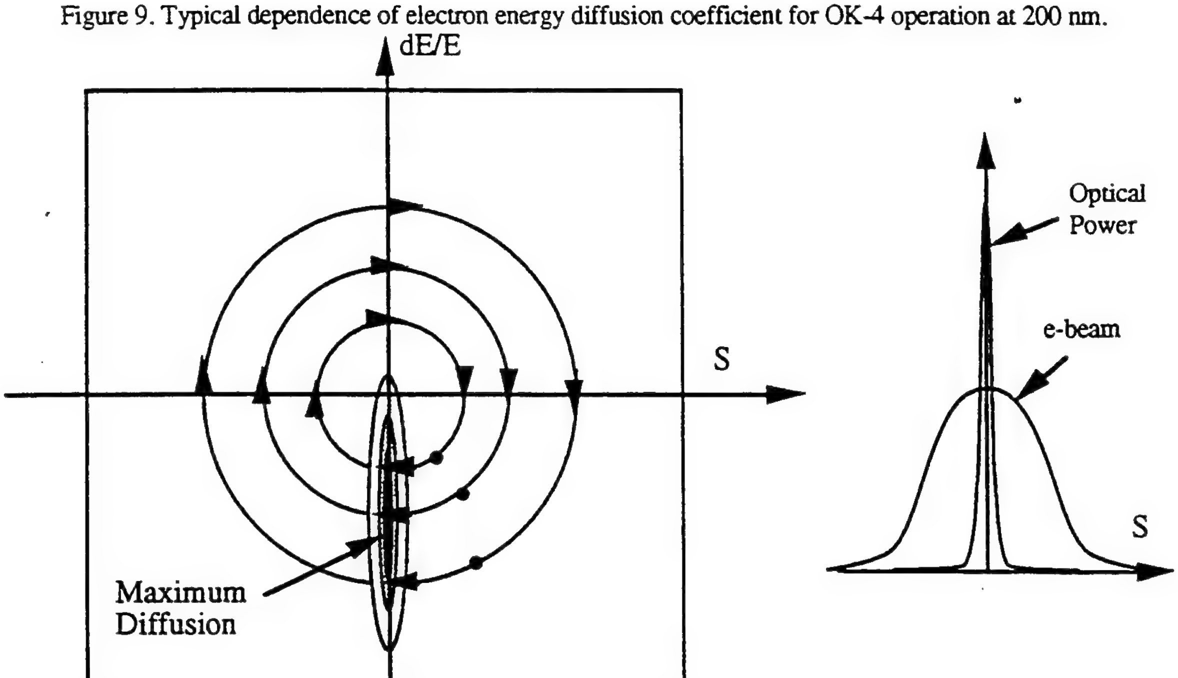

Figure 10. Qualitative explanation of phase-space e-beam refreshment and localized diffusion: Optical pulse is much shorter than electron bunch; it creates local hot spot (s-wise) where diffusion is maximum; energy diffusion is also energy dependent which makes most of the phase space "diffusion-free". Synchrotron oscillations move electrons clockwise and bring new, fresh electrons into the center where they interact with the optical pulse, amplify it, and diffuse.

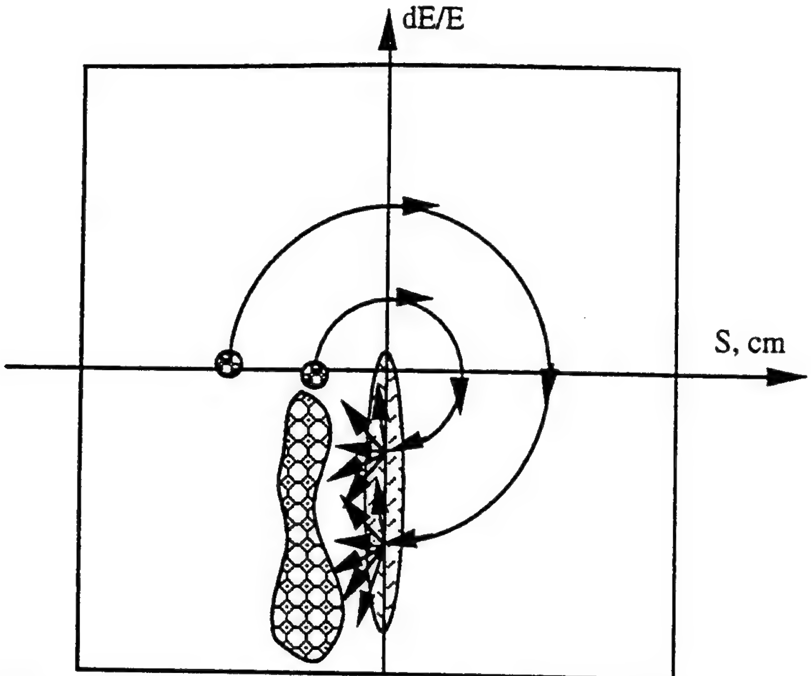

Figure 11. Fresh electrons come to the interaction point, cross the "hot spot" and diffuse.

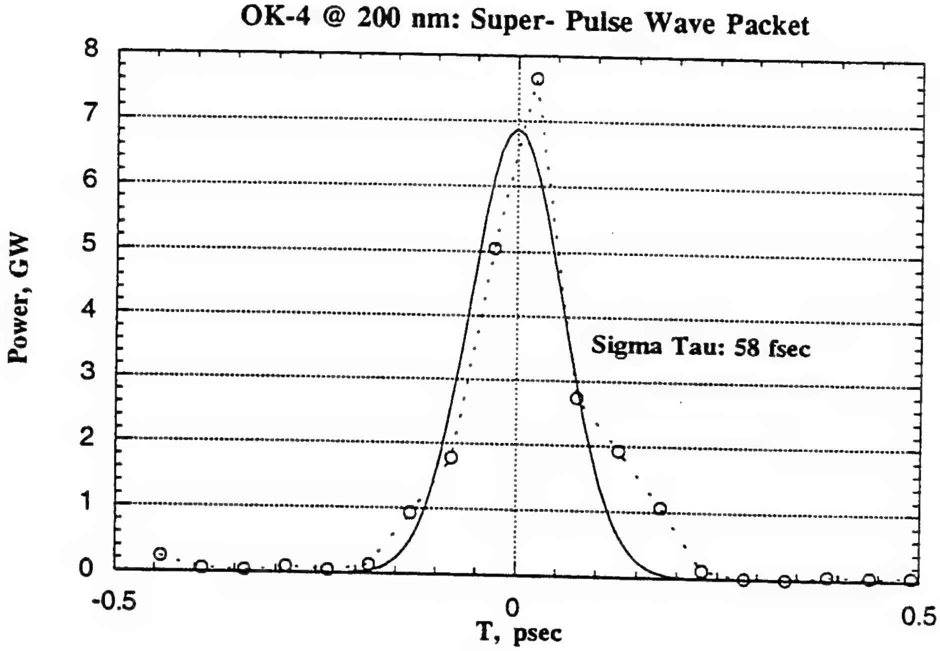

Figure 12. A spike with RMS width of 58 fsec at 200 nm. o - simulation data, solid line - Gaussian fit.

We also observed the influence of optical cavity detuning on the optical pulse shape and its relative position with respect to the electron bunch. In some cases we observed the growth of very short spikes with femtosecond duration. One of these spikes is shown in Fig. 12. We continue these studies for better understanding of these phenomena.

With more ambitious, but achievable, parameters of electron beam (average current of 92 mA and 1.5 MV RF voltage) the OK-4 can operate in the VUV range at 80 nm. Results are published elsewhere [2].

4. CONCLUSIONS

Simulations by a self-consistent storage ring FEL code have confirmed our general projections for the performance of the OK-4 FEL installed on the Duke Storage Ring. This code allows us to simulate all known effects in storage ring FELs. We discovered the new phenomenon of Super Pulse generation using this code and then explained it [15] by phase-space refreshment. Super Pulse mode of storage ring operation allows the achievement of 10 to 30 times higher peak power than was predicted by standard models [2]. The GW peak power levels and phase-space refreshment create favorable conditions for effective harmonic generation.

We plan to continue simulations and improve the code. Improvements of the code will include nonlinear FEL effects, harmonic generation, multiple transverse modes, and intracavity etalons.

The Duke storage ring is now fully operational. The OK-4 FEL is in the process of installation in the south straight section of the Duke ring. The commissioning of the OK-4 magnetic system with electron beam is scheduled for September, 1995. The start of lasing experiments in the deep UV is planned for December, 1995, when new end-of-arc vacuum chambers and optical cavity will be installed.

A gain modulator will be installed in March, 1996, to provide OK-4 UV/VUV FEL Giant pulse/Super pulse operation in the first half of 1996.

5.ACKNOWLEDGMENTS

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6. REFERENCES

[1] "Commissioning of the Duke Storage Ring", V.Litvinenko et al., In proc. of 1995 Particle Accelerator Conference, Dallas, Texas, May 1-5, 1995

[2] V.Litvinenko, B.Burnham, J.M.J.Madey, Y.Wu, Nucl.Instr.and Meth.,A358 (1995) 334-337

[3] V.N.Litvinenko, "The optical klystron on VEPP-3 storage ring bypass - lasing in the visible and the ultraviolet", Thesis, Novosibirsk, 1989; I.B.Drobyazko et al., Nucl.Instr.and Meth.,A282 (1989) 424

[4] J.B.Kortright, FEL Handbook, 1988

[5] B.E.Newnam, SPIE v.1227 (1990) 116

[6] N.A.Vinokurov and A.N.Skrinsky, Preprint INP 77-67, Novosibirsk, 1977, A. Renieri, Nuovo Cimento B *53* (1979) 160

[7] P.Elleaume, Thesis (1984, Universite Pari-Sud); M.Billardon et al., Nucl.Instr.and Meth.,A237 (1985) 38;

[8] "Duke storage ring FEL program", V.Litvinenko et al, SPIE Vol.1552 (1991) 2. "UV-VUV FEL Program at Duke storage ring with OK-4 optical klystron", V.Litvinenko, J.M.J.Madey and N.A.Vinokurov , IEEE PAC 1993, v.2, p.1442

[9] V.Litvinenko et al., IEEE J. of QE 27 (1991) 2560

[10] V.Litvinenko, B.Burnham, J.M.J.Madey, Y.Wu, Nucl.Instr.and Meth.,A358 (1995) 369-373

[11] V.Litvinenko, DFELL report, 1994

[12] G.Dattoli et al., Nuovo Cimento B58 (1980)

[13] V.Litvinenko, Nucl.Instr.and Meth.,A359 (1995) 50-56

[14] V.Litvinenko, Y.Wu, B.Burnham, J.M.J.Madey, Nucl.Instr.and Meth.,A358 (1995) 349

[15] "Physics of Super-pulses in storage ring FELs", V.Litvinenko, to be published.

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RF System for the Duke 1 GeV Storage Ring*

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Abstract

The RF frequency is 178.5 MHz. An amplifier built by the QEI corporation provides 50 KW power. All the power feeds to a single-cell RF cavity, built by BINP at Novosibirsk, Russia, giving a gap voltage of 720 KV. An ANT circulator is used in the feed line. There are four basic feed-back loops to stabilize the system operation : 1) Cavity frequency tuning loop. 2) Cavity voltage control loop. 3) RF phase stabilization loop. 4) Synchrotron oscillation damping loop. The whole system has been tested and operated since December 1993. It has provided secure and stable operation for the storage ring.

I. RF PARAMETERS

The main parameters of the RF system for the Duke storage ring are given in Table 1.

TABLE 1
RF system Parameters

Electron Beam Energy	1 GeV
Synchrotron radiation loss per turn	42KeV
Ring circumference	107.46 meter
Rf frequency	178.547 MHz
Harmonic Number	64
Available RF power	50 KW
Cavity shunt impedance	11 M Ohms
Cavity coupling coefficient	1.78
Maximum peak cavity voltage	720 KV
Cavity unloaded Q	40,000
Cavity frequency tuning rang	360 KHz

II. RF CAVITY

The RF cavity is made of copper-clad stainless steel. It is designed to have an operational capability of 200 KW CW power. The operating power is limited by its coupling loop which is not water cooled. The cavity itself has an adequate cooling water system. There are five cooling water channels around the cavity and a total water flow of 16 gallons per minute. Tests show a 20 KHz resonant frequency shift when the RF power to the cavity is raised from zero to 50 KW. The maximum temperature difference across the cavity wall is 18 degrees Centigrade at full power.

There are four mechanical plunger tuners on the cavity. Two tuners are for fundamental mode and the other two are designed to shift the high-order mode frequencies but not affect the fundamental mode. The two high order mode tuners are tuned manually in the control room for better beam stability. The two fundamental mode tuners are automatically adjusted to compensate for reactive beam loading and thermal deformation. they provide a total frequency tuning range of 360 KHz.

The cavity is fed by an air-filled coax line through a ceramic window. The coax line connected to the cavity has an impedance of 75 ohms. The rest of the coax lines are 50-ohms impedance. An impedance adapter from 50 to 75 ohms is installed between them.

A more detailed description about this cavity can be found in the reference [1].

III. POWER AMPLIFIER AND CIRCULATOR

The 50 kW output stage uses a single Eimac 4CW100000E tetrode with a water cooled plate. The tube is operated in a grounded grid configuration. Air cooling is used for the output cavity and the control grid. At full output, the stage gain is approximately 12 dB and the plate efficiency is typically 50%. The plate power supply input is 480 Volt, three phase delta, with twelve pole output to the rectifiers. This unregulated supply can deliver over 100 kW continuously at 8.5 KV. The output stage and its associated power supplies occupy two 19X78 inch cabinets. Sixteen solid state modular amplifiers drive the output tetrode via combiners. Each amplifier is rated at 250 Watts. The nominal stage gain is 14 dB. Two more of these modules are used as low level drivers, also with a 14 dB stage gain. These amplifiers are powered by nine switch mode regulated power supply modules. A solid state pre-amplifier with a maximum nominal output of 10 Watts provides an additional 40 dB of gain, so that full output can be achieved with an RF input of less than 1 mW. The solid state amplifiers, their associated power supplies and the control circuits are contained in two more cabinets.

A three port circulator rated at 150 kW was installed between the 50 kW amplifier and the RF cavity. The ports are all 6.125-inch EIA coax. The circulator was supplied by ANT

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Telecommunications Incorporated, and after sales service is being provided by Advanced Ferrite Technology. This circulator is fitted with arc detection and temperature compensation. The forward loss is under 0.15 dB and the isolation provided is greater than 20 dB. The circulator is connected to a regulated water circulating loop which maintains a temperature of 34 degrees centigrade at all times. Operation above ambient temperature ensures that water films are not formed on the ferrite surfaces in the circulator.

IV. CONTROL CIRCUITS

The control circuits deal with the control and stabilization of the amplitude and phase of the RF field in the cavity. Interlocks for the cooling water, cavity vacuum and personal safety are also provided. There are four feedback loops as follows:

1) Cavity frequency tuning loop:

This feedback loop compares the RF phase of the field in the cavity to the phase of the input signal to the cavity and uses the resulting difference to operate the tuners via a DC motor. The phase comparison is made by converting both RF signals to 2.79 MHz via a mixer; Then the phase is measured by the duty factor of the intermediate frequency output after the amplitude limiter. This phase detector circuit has a sensitivity of 50 mV / per degree. The same type of phase detectors are also used in the phase stabilization loop and synchrotron oscillation damping loop.

2) Cavity voltage control loop

This feedback loop compares the field amplitude detected from the cavity sampling loop to a fixed reference voltage. The resulting signal is applied to a gain-controlled amplifier in the drive line to the transmitter.

3) Phase stabilization loop

The main function of this loop is to lock the field vector in the RF cavity to the RF signal generator. The RF signal detected from the cavity sampling loop is compared with a reference signal which is derived from the RF generator. Its output signal is used to drive a phase shifter in the RF drive line. The phase shifter is made by two LC resonant circuits with two voltage variable capacitance (VVC) diodes as control elements. The phase range is over 360 degrees.

4) Synchrotron oscillation damping loop

This loop samples beam signal from one of the beam position monitors. After a frequency filter, the 178.5 MHz beam signal is compared with the reference signal in a phase detector. Its output signal is used to drive the same phase shifter in the phase stabilization loop. The loop has a frequency response of 4-20 KHz which covers all the synchrotron frequencies at different machine configurations.

The entire system can be operated locally or remotely by the EPICS (Experimental Physics and Industrial Control System, provided by Los Alamos National Laboratory) control system using Allen Bradley control hardware (see [2]). The operator can choose either of the following two operation modes in the control room. a) setting desired cavity voltage and cavity resonant phase, the system determines the RF power needed and stabilizes at that level. b) setting the coupling loop current which corresponds the RF power in the cavity, after the cavity voltage is chosen the system determines the resonant phase and vice versa.

This loop also keeps the phase of stored beam locked to the phase of RF generator which also is the source of timing system

V. OPERATION AND FUTURE PLANS

The RF system has been in operation with manual control since December of 1993. With on site support from QEI, ANT and BINP, the system was debugged and characterized. The control and read back circuits were integrated with the high level control system known as EPICS. In November 1994 the first stored beam was achieved and the optimum control settings were determined within a few weeks (see [3]).

Our long term objective is to increase the output power capability to 150 kW, at which point the circulator will become the limiting factor. In the near term there are some upgrades that are being considered.

The power supplies for the solid state amplifier stages generate noise at harmonics of the 20 KHz switching frequency. Harmonics derived from the line frequency are coming through the output tube plate supply. An inexpensive approach to reducing these noise sources is being studied.

To date we have not needed to run the amplifier above 15 kW for storage ring operations. Before full output can be used, power output stability must be improved. Water cooling the output cavity seems to be simple to implement and inexpensive, but other approaches are being considered.

of QEI

VI. ACKNOWLEDGMENT

The authors wish to thank Carl Dickey and Owen Oakeley for their helpful efforts on the electrical controls and interlock circuits, Joe Faircloth and Pat Cable for the installation of cavity, coax line and transmitter; their contributions are much appreciated.

References

[1]. V. Arbuzov, et al., "RF System of the CW Race-Track Microtron-Recuperator for FELs", Proc. 1993 IEEE PAC, Washington D.C., P1226, Vo. 2.

[2]. Y. Wu, et al., "The Duke Storage Ring Control System", these proceedings.

[3] V. N. Litvinenko, et al., "Commissioning of the Duke Storage Ring", these proceedings.

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

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Nuclear Instruments and Methods in Physics Research A 358 (1995) 334–337

Giant laser pulses in the Duke storage ring UV FEL ☆

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Giant laser pulses in the Duke storage ring UV FEL ☆

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Abstract

We have studied the dynamics of giant pulse generation in the Duke UV FEL with peak power of several gigawatts. The giant pulses will be provided by a FEL gain modulation technique developed for the OK-4 UV FEL at Novosibirsk, Russia. A new mechanism for "super-pulse" generation was discovered during these studies. It allows the generation of peak power up to 10 GW using the "phase space" refreshment of the electron beam caused by synchrotron motion [V. Litvinenko et al., to be published]. We have developed a new macro-particle code for giant pulse simulation including all known mechanisms of storage ring FEL interaction. Results of these giant pulse simulations are presented in the paper.

1. Introduction

The CW output of short wavelength storage ring FELs is limited by the energy spread growth of the electron beam due to its interaction with the FEL optical field [2]. Nevertheless, this power can be redistributed in time using a Q-switch technique [3] or gain modulation technique [4] to generate giant pulses with 0.1 to 1 GW level of power. The previous projections for the average and peak power performance of the OK-4 FEL, which will be shipped from the Novosibirsk Institute of Nuclear Physics to Duke in January 1995, have been published elsewhere [5].

To test our expectations we have developed a computer program which includes all known phenomena affecting storage ring FEL performance. The theory of storage ring FEL operation implemented in this program is published in these Proceedings [6]. In this paper we present a description of the code and summary of results for the OK-4/Duke UV/VUV FEL achieved using this code. During the study we discovered new phenomena – super pulses with ten to thirty times higher peak power than giant pulses. The theory of these phenomena and the main results on super pulses are presented in Ref. [1].

2. Computer model

We have developed a set of computer programs which include all known phenomena influencing operation of short-wavelength storage ring FELs (SRFEL). The high efficiency algorithms used in the code allow us to track up to 30 000 macro-particles for tens of thousands turns to simulate real-time self-consistent SRFEL operation. A detailed description of the codes is published elsewhere [7]. The model we use here simulates an optical klystron with total length $2L$ comprised of two planar undulators (each with N_u periods of λ_u and undulator parameter of K_u) and a buncher occupying a length from $-z_i$ to z_i [6]. The strength of the buncher can be adjusted to optimize FEL operation. With the buncher turned off the system becomes a conventional FEL.

Macro-particles. A macro-particle is described by its energy $\varepsilon = (E - E_0)/E_0$ and longitudinal position $s = cl_0$, where t_0 is the electron arrival time at $z = 0$. It represents a cluster of electrons localized in (ε, s) phase-space and having standard distribution in transverse phase space. As was shown in Ref. [6], radiation of the macro-particle can be found analytically. This analytical capability makes these simulations possible. The maximum number of macro-particles in the program is 30 000.

Optical Wavepacket. We represent the FEL optical field, $\boldsymbol{E}$, by a TEM_{00} mode with slowly varying complex amplitude $A_0(s)$.

$$\boldsymbol{E}_0(t, \boldsymbol{r}) = \mathrm{Re}\left\{ \hat{e}_x A_0(s) \frac{\beta_0}{\beta_0 - \mathrm{i}z} \exp\left[\mathrm{i}ks - \frac{k}{2} \frac{x^2 + y^2}{\beta_0 - \mathrm{i}z} \right] \right\}, \tag{1}$$

where $s = cl - z$ and c is the speed of light. The Rayleigh length is β_0 with waist at azimuth $z = 0$; x and y are transverse coordinates and $k = 2\pi/\lambda$ is the optical wave vector. An optical wave packet is represented by an array (with maximum length of 30 000) of complex wave amplitude $A[i]$. The length of one array bin is equal to the total

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slippage in the FEL $\Sigma_t = \Sigma(L) - \Sigma(-L)$ (see Eq. (3)). This choice limits wavelength bandwidth to $\Delta k \sim l/\Sigma_t$. This bandwidth is sufficient to include full width of the FEL gain profile. The program includes the energy detuning parameter which is set to the maximum gain.

FEL parameters. We use two complex arrays to represent individual macroparticle induced radiation. It is a well known that the induced radiation (both real and imaginary part of it) is shifted with respect to the optical wavepacket. This effect is essential for optical pulse evolution because it influences the super-mode structure [8]. This shift depends on electron energy. To properly model slippage of induced radiation, we used (in addition to the average value of real and imaginary part of the gain) the first moments of the real and imaginary parts of the gain:

$$G_m = \int_{\Sigma(-L)}^{\Sigma(L)} sA_{\text{ind}}(s)\,ds,$$

$$A_{\text{ind}}(s_0 + \Sigma(z)) = -i\frac{k}{E_0\beta_0}\left(\frac{eK_u\text{JJ}}{2\gamma}\right)^2\left(\frac{d\Sigma}{dz}\right)^{-1}\int_{-L}^{z} dz_1 \times A_0(s_0+\Sigma(z_1))(\Sigma(z)-\Sigma(z_1)) \times \text{FF}(z, z_1)\,e^{i(k_u(z-z_1)-k(\Sigma(z)-\Sigma(z_1)))}, \quad (2)$$

where $\Sigma(z)$ is the FEL slippage function:

$$\Sigma(z) = z\frac{1+K_u^2/2}{2\gamma^2}\begin{Bmatrix} - \\ + \end{Bmatrix}\frac{\Delta s_B}{2}\left(\frac{\gamma_0}{\gamma}\right)^2\begin{Bmatrix} z < -z_i \\ z > z_i \end{Bmatrix}, \quad (3)$$

and Δs_B is the slippage in the buncher. The function $\text{FF}(z_1, z_2)$ is a complex function derived analytically which takes into account the influence of both horizontal and vertical e-beam emittances and the TEM_{00} mode structure [6,10].

The spontaneous radiation is represented by an array with exact values of the radiation amplitude into one bin which is multiplied by the square root of the number of electrons in the macro-particle. We use the exact analytical expressions for spontaneous radiation into the TEM_{00} mode, including energy dependence and e-beam emittance [6]:

$$|A_{sp}|^2 = \frac{2k}{\beta_0}\left(\frac{eK_u\text{JJ}}{\gamma_0}\right)^2\int_{-L}^{L}\int_{-L}^{L} dz_1\,dz_2 \times \text{FF}(z_1, z_2)\,e^{i[k(\Sigma(z_1)-\Sigma(z_2))-k_u(z_1-z_2)]}, \quad (4)$$

where $k_u = 2\pi/\lambda_u$. Before adding this expression to the wavepacket, the amplitude of the spontaneous radiation is multiplied by a random number with unit RMS value and complex exponent with random phase. A very similar algorithm is used for the random energy kick caused by the FEL interaction. This energy kick is represented by an array of exact RMS kick values. The amplitude of the kick depends on the amplitude of the local optical field (see Ref. [6]) and is random in phase:

$$\langle\Delta E^2\rangle = \frac{1}{2}\left(\frac{eK_u\text{JJ}}{2\gamma_0}\right)^2|A_0|^2\int_{-L}^{L}\int_{-L}^{L} dz_1\,dz_2 \times \text{FF}(z_1, z_2)\,e^{i[k(\Sigma(z_1)-\Sigma(z_2))-k_u(z_1-z_2)]}. \quad (5)$$

Each of the arrays described above contains 10001 values for a 4% energy deviation range with a step of $\delta\gamma/\gamma = 4\times10^{-6}$. In order to optimize the FEL performance we provide the capability to interactively change slippage in the buncher and energy detuning. For a chosen FEL geometry, wavelength, and central electron energy, a special program tabulates one real and eight complex double integrals [10] required for the four arrays described above as functions of electron energy, with an energy step of 4×10^{-6}. These integral data are saved in a file. These integral calculations take about one hour of CPU time on a SPARC workstation. The main program reads this file and produces in a few seconds all of the necessary arrays for chosen slippage of the buncher, and recommends the optimum energy detuning parameter.

The main program is composed of four main subroutines:

FelCoefficients – Reads tabulated integrals and calculates arrays of real and imaginary values of macro-particle gain and moments. It also recommends the optimum value of energy detuning.

RingPass – Includes the exact algorithm for round trip pass of the macro-particle around the storage ring described in Ref. [9].

FelInteraction – The main part of the code. It finds the two wavepacket bins the particle is interacting with and calculates the wavepacket optical field using the linear (small signal) approximation. It also calculates the energy bin corresponding to the instantaneous value of the macro-particle energy (including energy detuning). Next it adds the spontaneous radiation (from the proper energy bin) into the wavepacket bins proportional to their overlap (see Fig. 1). The induced radiation is calculated (from the proper energy bin ε – bin) using the complex gain g_{av}, its first moment g_{mom}, and optical wave amplitude A_0:

$$A_0 = A[i](1-X) + A[i+1]X,$$

$$A[i] = A[i] + A_0(1-X)\{g_{av}[\text{e\_bin}] - g_{mom}[\text{e\_bin}]X\},$$

$$A[i+1] = A[i+1] + A_0X\{g_{av}[\text{e\_bin}] + g_{mom}[\text{e\_bin}](1-X)\}, \quad (8)$$

where X is the overlap of macro-particle radiation and wave-packet bins (see Fig. 1). Finally, the program varies the electron energy using the energy kick array, optical wave amplitude, and random phase.

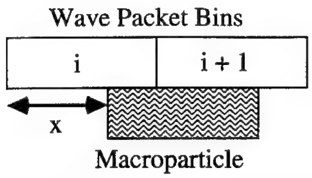

Fig. 1. Optical wave and electron bin overlap.

CavityPass – implements exact transformation as described by:

$$A_{n+1}(s) = \sqrt{R}\, A_n(s - d), \tag{9}$$

where R is the round trip reflectivity and d is the detuning of the optical cavity. It accumulates the total value of the detuning from pass to pass and moves the wavepacket array only for the integer part of accumulated detuning. It passes the non-integer part into the FelInteraction subroutine. There it is taken into account in the bin search and interaction. The algorithm is described in Ref. [7]. Additional subroutines provide file service and interactive mode of operation. Some of the FEL parameters are used by the program to tabulate integrals. Other parameters in the code can be changed interactively without the one hour delay for tabulation of integrals. While interactive operation complicates the tabulation program (nine integrals instead of three), it gives the very important advantage of flexibility and speed.

3. Results of giant pulse simulations

Using the codes described above, we studied laser pulse and e-beam dynamics of the OK-4/Duke UV FEL in Giant pulse mode in the deep UV and VUV range. The parameters of electron beam and layout of the storage ring and OK-4 UV/VUV FEL are published in Refs. [6,11]. We assume an e-beam current of 10 to 100 mA average current (typical value 46 mA) and 10-100 A peak current.

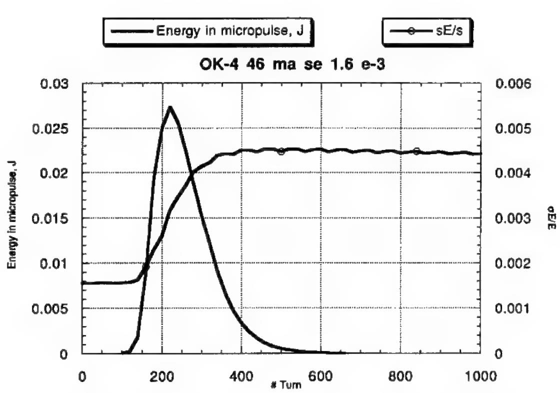

Fig. 2. OK-4 FEL optical micropulse energy and e-beam energy spread evolution during a giant pulse.

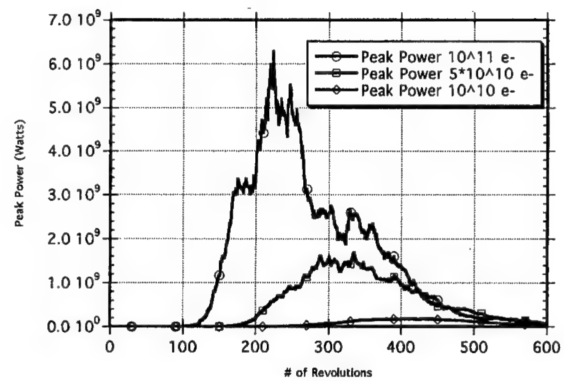

Fig. 3. Peak power in OK-4 FEL at 200 nm for different beam currents (4.6, 23 and 46 mA).

Giant pulse mode in the OK-4/Duke FEL will be realized using gain modulation [4]. The electron beam will be displaced by a special deflector from the axis of the optical cavity to reduce FEL gain below cavity losses. The cooled beam, with energy spread defined by microwave instabilities (see Ref. [6]), will return back to the axis during 50 to 100 e-beam revolutions to ensure adiabatic transition of the closed orbit and absence of residual betatron oscillations. Thus, the FEL will start from noise and the laser power will grow exponentially until it starts to heat the beam. As the energy spread grows, the FEL gain decreases. Maximum power will be reached when FEL net gain is zero. The heated e-beam will be deflected from the axis for 2–4 damping times (15–30 ms for 1 GeV operation) to be cooled. The giant pulse may then be repeated.

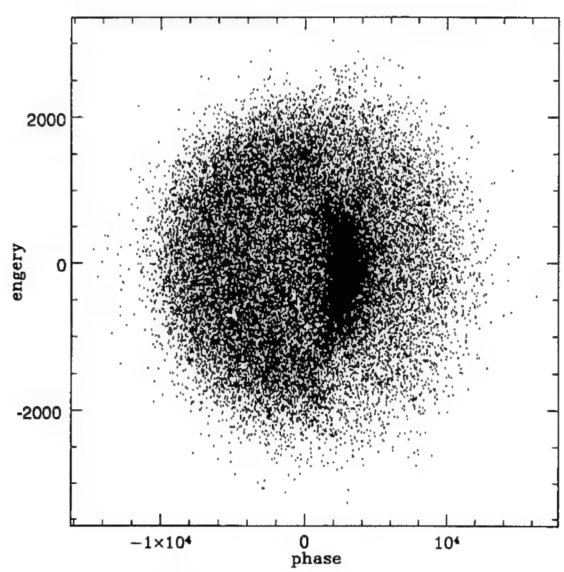

Fig. 4. Poincare (E, s) phase-space plot for super pulse mode of the OK-4 FEL.

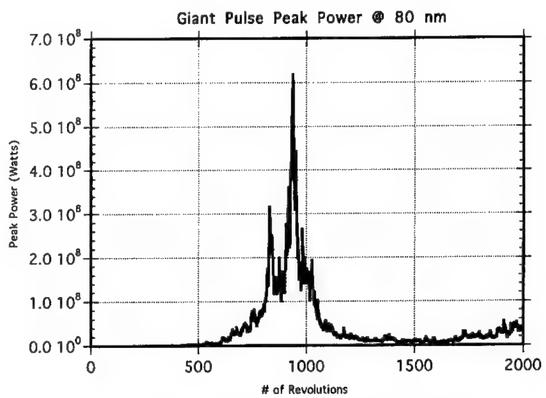

Fig. 5. OK-4 FEL optical micropulse energy at 80 nm.

A typical giant pulse shape for the OK-4/Duke FEL operating at 46 mA (10^{11} electrons) at 200 nm is shown in Fig. 2. Fig. 3 shows the optical peak for the same beam parameters in the super pulse regime [1]. A typical Poincare plot for this mode of operation is shown in Fig. 4. While the energy in the micropulse in these simulations corresponds to earlier theoretical predictions [5], the peak power is 10 times higher than expected. This fascinating discrepancy is caused by the "super pulse" phenomena [1] and can be exploited for production of very short pulses with exceptionally high peak power.

With more ambitious, but achievable, parameters of electron beam (average current of 92 mA and 1.5 MV RF voltage) the OK-4 can operate in the VUV range at 80 nm. The regular optical cavity must be replaced with a multifacet ring resonator [12]. Fig. 5 shows the OK-4 giant pulse at 80 nm with 14% roundtrip losses in the optical resonator.

We also observed influence of optical cavity detuning on the optical pulse shape and its relative position with respect to the electron bunch.

4. Conclusions

Simulations of giant pulses by a self-consistent storage ring FEL code have confirmed our general projections for the performance of the OK-4 FEL installed on the Duke Storage Ring. In addition, the new phenomena of super pulses generation was discovered using this code and then explained [1]. Super pulse mode of storage ring operation allows the achievement of 10 to 30 times higher peak power than was predicted by standard models [2].

We plan to continue simulations and improve the code. Improvements of the code will include nonlinear FEL effects, harmonic generation, multiple transverse modes, and intracavity etalons.

References

[1] V. Litvinenko, B. Burnham, J.M.J. Madey and Y. Wu, Super pulses in storage ring FELs, submitted to Phys. Rev. Lett.

[2] N.A. Vinokurov and A.N. Skrinsky, Preprint INP 77-67, Novosibirsk (1977);
A. Renieri, Nuovo Cimento B 53 (1979) 160.

[3] P. Elleaume, Thesis, Universite Paris, Sud (1984);
M. Billardon et al., Nucl. Instr. and Meth. A 237 (1985) 38;

[4] V.N. Litvinenko, The optical klystron on VEPP-3 storage ring bypass – lasing in the visible and the ultraviolet, Ph.D., Novosibirsk (1989);
I.B. Drobyazko et al., Nucl. Instr. and Meth. A 282 (1989) 424.

[5] V. Litvinenko et al., SPIE Vol. 1552 (1991) 2;
V. Litvinenko, J.M.J. Madey and N.A. Vinokurov, IEEE PAC 1993, vol 2, p. 1442.

[6] V. Litvinenko, B. Burnham, J.M.J. Madey and Y. Wu, these Proceedings (16th Int. Free Electron Laser Conf., Stanford, CA, USA, 1994) Nucl. Instr. and Meth. A 358 (1995) 334.

[7] V. Litvinenko, DFELL report (1994).

[8] G. Dattoli et al., IEEE J. Quantum Electron. QE-17 (1981) 1371.

[9] V. Litvinenko, Y. Wu, B. Burnham, G. Barnett and J.M.J. Madey, these Proceedings (16th Int. Free Electron Laser Conf., Stanford, CA, USA, 1994) Nucl. Instr. and Meth. A 345.

[10] V. Litvinenko, Proc. Nat. Synchrotron Radiation Conf. SR-94, Novosibirsk, July 11–15, 1994, to be published in Nucl. Instr. and Meth.;
V. Litvinenko, Analitical derivation of 3D FEL time-dependent (complex) gain matrix and spontaneous radiation, to be published.

[11] Y. Wu et al., Nucl. Instr. and Meth. A 331 (1993) 287;
Y. Wu et al., IEEE PAC 1993, vol. 1, p. 218.

[12] B.E. Newnam, SPIE 1227 (1990) 116.

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FINAL TECHNICAL REPORT

AFOSR Grant No. F49620-93-1-0590

For period of 30 September 1993 to 28 March 1997

Principal Investigator: **John M.J. Madey**
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* Principal Investigator is out of town at this time and I was requested to prepare this report by the Duke University Office of Research Support.

Summary:

The research supported by this contract has been focused on the physics relevant to the construction and the use of state-of-the art high current, high brightness, ultra-relativistic electron beams in the energy range from 0.25 GeV to 1.1 GeV, namely, the 1 GeV Duke storage ring system. At the present time, the Duke storage ring has been commissioned and has been used for the production of coherent UV radiation from the OK-4 XUV FEL, production of spontaneous X-ray radiation, and production of a monochromatic γ-ray beam.

A number of very successful theoretical results have been developed and many of them have been tested. Most objectives specified in the proposal have been achieved. More then fifty publications (listed in the attachment) have been generated during this period with AFOSR support. A number of initial objectives for the Duke storage ring have been exceeded during the commissioning of the storage ring and its subsystems.

This research has led to the creation of a unique facility capable of producing high brightness electron beams with parameters exceeding initial design goals. These beams have been utilized for ground-breaking achievements with the OK-4 FEL system, including the first-and-only UV FEL in the US and the first-and-only monochromatic γ-ray beam with tunable energy.

Special recognition for these outstanding accomplishments should be accorded to the storage ring group: Drs. Y. Wu, I.V. Pinayev, B. Burnham, P. Wang and P. O'Shea; graduate student S.H. Park; talented engineers and technicians: M. Emamian, J. Faircloth, S. Goetz, N. Hower, J. Meyer, P. Morcombe, O. Oakeley, J. Patterson, R. Sachtschale, G. Swift and a number from collaborating institutions.

Two Ph.D.s (by Dr. Y. Wu: "Theoretical and experimental studies of the beam physics in the Duke FEL Storage Ring," and by Dr. B. Burnham: "Storage ring Free Electron Lasers: Dynamics and Characteristics") based on research supported by AFOSR have been defended during this period.

The Attached list of publication provides detailed information on the breadth, depth and successfulness of the reported research.

Accomplishments:

The experimental achievements made during this grant in most cases confirmed our theoretical models and predictions. During this grant the following elements of the work statement were accomplished. Publications describing these accomplishments are given in brackets.

• Commissioning the injection system for the Duke Ring	• **Completed in November 1994 [46]**
• Commissioning the Ring at 300 MeV injection energy	• **Completed in November 1994 [44]**
• Raise the injection energy and operating energy of the ring as additional accelerator sections and modulators are installed.	• **An energy of 1.1 GeV (exceeding design goal of 1 GeV) has been achieved in the storage ring using ramping, Jan. 1995 [6, 46].**
• Study the performance of the lattice of the Duke ring as it relates to electron beam emittance, emittance growth, chromatic effects and the dynamic aperture, and use in service as an UV/XUV FEL light source.	• **Studies of the Duke Storage Ring performance were conducted during 1994-1995 They confirmed our theoretical predictions for the emittance and chromatic effects. The results of these studies are reported in References [2-4,6,7,11,19,22,24-28,39-46] and two Ph.D.s**
• Study the non-linear resonances and non-linear tuning predicted by theory for the Duke ring.	• **Studies in 1994-1995 proved our theoretical predictions. The results are reported in References [6,19,39] and the Ph.D. thesis of Dr. Y. Wu.**
• Study the threshold and strengths of the coherent synchrotron oscillations in the Duke ring and the use of feedback to suppress these oscillations.	• **Studies were performed in 1994-1996. The feed-back system for the dipole mode of oscillation was commissioned in 1995 and is currently operational. Multibunch coherent oscillations were observed. In a number of modes these oscillation could be suppressed with the use of high order mode tuners in the RF cavity. The results are reported in References [45,6,19,39].**
• Study the causes and characteristics of bunch lengthening in the Duke ring including the modeling of impedances, extent (if any) of energy spread, and effects of FEL operation.	• **Our studies in 1995-1996 confirmed our broad band impedance model for bunch lengthening with Z/n=2.5 Ohm. In 1996 we studied the effects of bunch lengthening and energy spread during FEL operation. UV FEL micropulses as short as 2.5 psec have been observed. The results are reported in References [1-4,6,24-27]. A new theoretical approach to suppress microwave instability has been proposed in Ref. [23]. Further research is required to verify this result.**

• Study the possible transverse instabilities including the identification of the threshold currents for the lowest order instabilities, the modeling of these instabilities, and the use of feedback to suppress these instabilities.	• **Studies in 1995 demonstrated that transverse head-tail instabilities occur with beam currents as low as 0.5 mA per bunch with natural chromatically. This instability could be suppressed using a setting of the chromatic sextapoles determined by our theory and currents of 155 mA have been stored. Discussion of head-tail instabilities are found in the following Refs. [6,19,39]**
• Evaluate the cost-effectiveness of the magnet, vacuum chamber, and RF hardware available to improve the current, emittance and energy spread.	• **A large number of cost effective designs and configurations have been studied and developed. Many of them have been implemented. Details are published in Ref. [1,10,17,23,34,37,39,45,47,53]**

The attached copies of selected publications which report the research supported by this grant provide more in-depth information.

ATTACHMENT 1.

List of Publication generated during reported period with AFOSR support

1. "OK-4/Duke monochromatic γ-ray performance and predictions", *S.H.Park, V.N.Litvinenko, B.Burnham, Y.Wu, J.M.J.Madey, R.S.Canon, C.R.Howell, N.R.Roberson, E.C.Schreiber, M.Spraker, W.Tornow, H.R.Weller,* accepted for publication in Nucl.Instr. Meth.

2. "Initial Dual-Sweep Streak Camera Measurements on the Duke Storage Ring OK-4UV/visible FEL" *A.H.Lumpkin and B.X.Yang, V.Litvinenko, S.Park, Y.Wu, B.Burnham, and P.Wang*accepted for publication in Nucl.Instr. Meth.

3 "First UV/Visible Lasing with the OK-4/Duke Storage Ring FEL", *V. N. Litvinenko, B. Burnham, S. H. Park, Y. Wu, M. Emamian, J. Faircloth, S. Goetz, N. Hower, J. M. J. Madey, J. Meyer, P. Morcombe, O. Oakeley, J. Patterson, R. Sachtschale, G. Swift, P. Wang, I. V .Pinayev, M. G. Fedotov, N. G. Gavrilov, V. M. Popik, V. N. Repkov, L. G Isaeva, G. N. Kulipanov, G.Ya.Kurkin, S. F. Mikhailov, A. N. Skrinsky, N. A. Vinokurov, P. D. Vobly, E. I. Zinin, A. Lumpkin, B. Yang*, accepted for publication in Nucl.Instr. Meth.

4. "Gamma-ray Production in a Storage Ring Free Electron Laser", *V.N.Litvinenko, B.Burnham, S.H.Park, Y.Wu, M.Emamian, N.Hower, J.M.J.Madey, P.Morcombe, P.G.O'Shea, R.Sachtschale, G.Swift, P.Wang, R.S.Canon, C.R.Howell, N.R.Roberson, E.C.Schreiber, M.Spraker, W.Tornow, H.R.Weller, I.V.Pinayev, N.G.Gavrilov, M.G.Fedotov, G.N.Kulipanov, G.Y.Kurkin, S.F.Mikhailov, V.M.Popik, A.N.Skrinsky, N.A.Vinokurov B.E.Norum, A.H.Lumpkin, B.Yang* Physics Review Letters, Volume 78, Number 4, 16 June 1997, p.4569-1472

5. "The Compton scattering process and radiotherapy", *K.J.Weeks, V.Litvinenko, J. Madey*Medical Physics 24 (3) March 1997 pp. 417-423

6. "Performance and Operation Modes of the Duke FEL Storage Ring", *Y.Wu, V.N.Litvinenko, B.Burnham, S.H.Park and J.M.J.Madey,* IEEE Transaction on Nuclear Science, Vol. 44, No. 5, 1997, p.1

7. "Duke Storage Ring UV/VUV FEL: Status and Prospects" *V.N.Litvinenko, B.Burnham, J.M.J. Madey, Y.Wu,* Nuclear Instruments and Methods A375 (1996) 46-52, **Invited Paper**

8. "VUV Optical Ring Resonator for the Duke Storage Ring Free Electron Laser", *S.H.Park, V.N.Litvinenko, J.M.J.Madey, B.E.Newnam,* Nucl. Instr. and Meth. A375 (1996) 487-491

9. "Intense Compton γ-Ray Source from the Duke Storage Ring FEL", *V.N.Litvinenko, J.M.J.Madey,* Nuclear Instruments and Methods A375 (1996) 580-583

10. "Resonant Conditions for Storage Ring Short Wavelength FEL with Power Exceeding Renieri Limit", *V.N.Litvinenko,* Nucl. Instr. and Meth. A375 (1996) 584-588

11. "The Performance the Duke FEL Storage Ring", *Y.Wu, V.N.Litvinenko, B.Burnham, J.M.J. Madey, S.H.Park,* Nucl. Instr. and Meth. A375 (1996) 74-77

12. "Picosecond Pump-Probe Using an FEL and Synchrotron Source", *G.Denbeaux, K.D.Straub, P.G.O'Shea, V.N.Litvinenko, J.M.J.Madey, E.Szamers, G. Barnett.* Nucl. Instr. and Meth. A375 (1996) 644-646

13. "Inverse Compton Gamma-Ray Source for Nuclear Physics and related Applications at the Duke FEL", *P.G.O'Shea, V.N.Litvinenko, J.M.J.Madey, N.R.Roberson, E.C.Schreiber, K.D.Straub, K.J.Weeks, H.R.Weller, Y.Wu,* Nucl. Instr. and Meth. A375 (1996) 530-534

14. "Status and projected performance of the Duke FEL lab soft X-Ray source", L.Johnson, J.M.J.Madey, K.D.Straub and V.N.Litvinenko, Rev. Sci. Instrum. 67 (9), Sept. 1996

15. "The TUNL-FELL inverse Compton γ-ray source as a nuclear physics facility",*T.S.Carman, V.Litvinenko, J.Madey, C.Neuman, B.Norum. P.O'Shea, N.R.Roberson. C.Y.Scarlett, E.Schreiber, H.Weller,* Nucl. Instr. and Meth. A378 (1996) 1

16. "Giant laser pulses in the Duke storage ring UV FEL", *V.N.Litvinenko, B.Burnham, J.M.J. Madey, Y.Wu,* Nucl. Instr. and Meth. A358 (1995) 334-337

17. "Expected performance of the mm-Wave isochronous FEL at the Duke storage ring", *V.N.Litvinenko, Y.Wu, B.Burnham, J.M.J. Madey,* Nucl. Instr. and Meth. A358 (1995) 349-352

18. "mm-Wave isochronous FEL and hard X-ray inverse Compton source at the Duke storage ring"*V.N.Litvinenko, Y.Wu, B.Burnham, G.Barnett, J.M.J. Madey,* Nucl. Instr. and Meth. A358 (1995) 345-348

19 ."Dynamics of the Duke storage ring UV FEL", *V.N.Litvinenko, B.Burnham, J.M.J. Madey, Y.Wu,* Nucl. Instr. and Meth. A358 (1995) 369-373

20. "UV-VUV FEL Program at Duke Storage Ring with OK-4 optical klystron", *V.N.Litvinenko, J.M.J.Madey, N.A.Vinokurov,* Proc. of 1993 IEEE Particle Accelerator Conference, Washington, DC, May 17-20, 1993, pp. 1442-1445

21. "3D free electron laser gain for an electron beam with finite emittance and energy spread" *V.Litvinenko*, Nucl. Instr. and Meth. A359 (1995) 50-56

22. "Study of Undulator Influence on the Dynamic Aperture study for the Duke FEL storage ring"*Y.Wu, V.N.Litvinenko, J.M.J.Madey,* Nucl. Instr. and Meth. A341 (1994) 363-366

23. "On a Possibility to Suppress Microwave Instability in Storage Rings using Strong Longitudinal Focusing", *V.N.Litvinenko*, Proc. of ICFA Workshop on Nonlinear and Collective Phenomena in Beam Physics", Arcidosso, Italy, September 2-6, 1996, AIP Conference Proceedings 395 (1997) pp. 275-284

24. "Initial Application of a Dual-Sweep Streak Camera to the Duke Storage Ring OK-4 Source", A. H. Lumpkin, B. X. Yang, V.N. Litvinenko, S.H. Park, P.Wang and Y. Wu,Proc. of the 1997 Particle Accelerator Conference, 12-16 May 1997, Vancouver, BC, Canada, In press

25. "Unique features of the OK-4/Duke storage ring XUV FEL and monochromatic γ-Ray source", V.N. Litvinenko, Y.Wu, B.Burnham, S.H.Park, M.Emamian, J.Faircloth, S.Goetz, N.Hower, J.M.J.Madey, J.Meyer, P.Morcombe, O.Oakeley, J.Patterson, R.Sachtschalle, G.Swift, P.Wang, I.V.Pinayev, M.G.Fedotov, N.G.Gavrilov, V.M.Popik, V.N.Repkov, L.G.Isaeva, G.N.Kulipanov, G.Ya.Kurkin, S.F.Mikhailov, A.N.Skrinsky, N.A.Vinokurov, P.D.Vobly, E.I.Zinin, A.Lumpkin, B.Yang, Proc. of the 1997 Particle Accelerator Conference, 12-16 May 1997, Vancouver, BC, Canada

26. "Status of the OK-4/Duke University Storage Ring XUV FEL", B.Burnham, V.N.Litvinenko,

Y.Wu, S.H.Park, R.Cataldo, M.Emamian, N.Hower, J.M.J.Madey, P.Morcombe, O.Oakeley, G.Swift, P.Wang, I.V.Pinayev, V.M.Popik, G.N.Kulipanov, S.F.Mikhailov, A.N.Skrinsky, N.A.Vinokurov, A.Lumpkin, B.Yang, Symposium on Optical Science, Engineering and Instrumentation, San Diego, CA, USA, 27 July-1 August 1997, SPIE Vol. 3154 (1997).

27. "First UV/visible lasing with the OK-4/Duke storage ring FEL: design and initial performance" *V.N.Litvinenko, Y.Wu, B.Burnham, S.H.Park, M.Emamian, J.Faircloth, S.Goetz, N.Hower, J.M.J.Madey, J. Meyer, P.Morcombe, O.Oakeley, J.Patterson, R.Sachtschale, G.Swift, P.Wang, I.V.Pinayev, M.G.Fedotov, N.G.Gavrilov, V.M.Popik, V.N.Repkov, L.G.Isaeva, G.N.Kulipanov, G.Ya.Kurkin, S.F.Mikhailov, A.N.Skrinsky, N.A.Vinokurov, P.D.Vobly, A.Lumpkin, B.Yang*, Proc. of the "Free-Electron Laser Challenges" Conference, San Jose, CA, 13-14 February, 1997, Ed. H. Bennet, SPIE Volume 2988 (1997) pp. 188-199 **Invited**

28. "Duke Storage Ring FEL: Status and Prospects", *V.N.Litvinenko, B.Burnham, J.M.J.Madey, S.H.Park, Y.Wu*, In Proc. of 10th ICFA Beam Dynamics Workshop "4th Generation Light Sources", Grenoble, France, January 22-25, 1996, pp. WG1.42-WG1.46

29. "Coherent X-Ray Harmonics Generation in Storage Ring FELs operating in Super-Pulse Mode" *V.N.Litvinenko*, , In Proc. of 10th ICFA Beam Dynamics Workshop "4th Generation Light Sources", Grenoble, France, January 22-25, 1996, pp. WG1.47-WG149

30. "X-Ray Storage Ring FELs: new concepts and directions", *V.N.Litvinenko*, , In Proc. of 10th ICFA Beam Dynamics Workshop "4th Generation Light Sources", Grenoble, France, January 22-25, 1996, pp. WG5.16-WG521

31. "Duke XUV Storage Ring FEL and Coherent X-Ray Harmonics Generation", *V.N.Litvinenko*, In Proc. of International Workshop on Generation and Application of Coherent X-Rays, KEK, Tsukuba, Japan, February 29-March 1, 1996, pp. 282-295

32. "Storage Ring Sources, Comments on X-Ray Coherence", *V.N.Litvinenko*, In Proc. of International Workshop on Generation and Application of Coherent X-Rays, KEK, Tsukuba, Japan, February 29-March 1, 1996, pp. 569-581

33. "Microbunching in Storage Ring FELs", *B.Burnham, V.N.Litvinenko, J.M.J.Madey, Y.Wu*, AIP Conf. Proceedings, Editors E.B.Blum, M.Dienes, J.B.Murphy, AIP 367 (1996) 215-224

34. "Short-wavelength light sources at Duke", *V.N.Litvinenko, G. Barnett, B.Burnham, N.Hower L.Johnson, J.M.J.Madey, Y.Wu*, Proc. of SPIE's International Symposium on Optical Science, Engineering & Instrumentation, San Diego, 9-14 July 1995, SPIE Vol. 2522 (1995) pp. 473-482.

35. "Picosecond pump-probe using a FEL and synchrotron source", D.Straub, J.M.J.Madey, P.O'Shea, V.N.Litvinenko, E.Szamers, G. Barnett, Proc. of SPIE's International Symposium on Optical Science, Engineering and Instrumentation, San Diego, 9-14 July 1995, SPIE Vol. 2522 (1995) pp. 468-472

36. "Picosecond, tunable, high peak brightness hard X-ray inverse Compton source at Duke storage ring", *V.N.Litvinenko, Y.Wu, B.Burnham, G.Barnett, J.M.J. Madey*, Proc. of SPIE's International Symposium on Optical Science, Engineering and Instrumentation, San Diego, 9-14 July 1995, **Invited Paper**, SPIE Vol. 2521 (1995) p.2-12.

37. "High Power Inverse Compton γ-Ray source at Duke Storage Ring", *V.N.Litvinenko, J.M.J.Madey*, Proc. of SPIE's International Symposium on Optical Science, Engineering and Instrumentation, San Diego, 9-14 July 1995, SPIE Vol. 2521 (1995) p.55-77

38. "High peak pulse power operation of the OK-4 Duke XUV FEL", *V.N.Litvinenko, B.Burnham, J.M.J. Madey, Y.Wu,* Proc. of SPIE's International Symposium on Optical Science, Engineering and Instrumentation, San Diego, 9-14 July 1995, SPIE Vol. 2521 (1995) p. 78-89.

39. "Application of Precision Magnetic measurements for control of Duke Storage ring", *B. Burnham, V.N. Litvinenko, Y. Wu,* Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995. p.524

40. "Experimental Study of the Duke Storage Ring Dynamic Aperture", *Y.Wu, V.N.Litvinenko, B.Burnham,* Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p.2877

41. "The Duke Storage Ring Control System", *Y.Wu, B.Burnham, V.N.Litvinenko,*Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p.2214

42. "Accelerator Archeology - The Resurrection of the Stanford MARKIII Electron Linac at Duke"*P. O'Shea, F.Carter, C.Dickey, N.Hower, V.N.Litvinenko, R.Sachthschale, G.Swift, P.Wang, Y.Wu, J.M.J. Madey,* Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p.1090

43. "EPICS at Duke University"", *C.Dickey,B.Burnham, F.Carter, R.Fricks, V.Litvinenko, A.Nagchaudhuri, P.Morcombe, R.Pantazis, P. O'Shea, R.Sachthschale, Y.Wu*Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p.2217

44. "Performance of achromatic lattice with combined function sextupoles at Duke storage ring""*V.N.Litvinenko, Y.Wu, B.Burnham, J.M.J. Madey, S.H.Park*Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p.796

45. "RF System for the Duke 1 GeV Storage Ring", *P.Wang, P.Morcombe, Y.Wu, G.Kurkin*Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p.1841

46. "Commissioning of the Duke Storage Ring", *V.N.Litvinenko, Y.Wu, B.Burnham, J. Madey, M.Emamian, J.Gustavsson, N.Hower, P.Morcombe, S.H.Park, P. O'Shea, R.Sachthschale, K.D.Straub, G.Swift. P.Wang, J.Widgren,* Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p.213

47. "Duke storage ring tune measurements system using razor blade and photomultiplier", *V.N.Litvinenko, B.Burnham, P.Morcombe, Y.Wu,* Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p.2461

48. "Critical Issues Involved in the Choice of a Driver for High-Power-Short-Wavelength CW FELs", *V.Litvinenko*, Proc. of OE/LASE' 95 SPIE'S International Symposium, San Jose, CA, 8-9 February 1994, *SPIE Vol. 2376 (1995).125-139*

49. "Component Technologies for a Recirculating Linac Free-Electron Laser", **INVITED** *V.Litvinenko, J.M.J.Madey, N.A.Vinokurov, SPIE Vol. 2121 (1994).21-37*

50. "DUKE FELL Storage Ring Gamma Rays Facility", *V.Litvinenko*, Materials of TUNL Workshop on the Development of a Polarized Gamma-Ray Beam, Durham, NC, December 16-17, 1994

51. "Bunch Current Density Measurements In The VUV Light Source", *S.Kramer, Y.Wu, V.N.Litvinenko, C.B.McKee, B.Burnham,* Proc. of 4th European Particle Accelerator Conference, London, UK , 27 June-1 July, 1994

52. "Lattice and Dynamic Aperture of the Duke FEL Storage Ring", *Y.Wu, V.N.Litvinenko, J.M.J.Madey*, Proc. of the 1993 IEEE Particle Accelerator Conference Washington, DC, May 17-20, 1993 pp. 218-220

53. "Specific features of magnetic design for Duke FEL storage ring", *B.Burnham, N.Hower, V.N.Litvinenko, J.M.J. Madey, Y.Wu*, Proc. of 1993 IEEE Particle Accelerator Conference, Washington, DC, May 17-20, 1993, pp. 889-2891